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Development and applications in computational fluid dynamics modeling for secondary settling tanks over the last three decades: A review

Haiwen Gao, Michael K. Stenstrom*

Department of Civil and Environmental Engineering, University of California Los Angeles, Los Angeles, CA, USA

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Correspondence to: Michael K. Stenstrom, Department of Civil and Environmental Engineering, University of California Los Angeles, Los Angeles, CA, USA.
Email: stenstro@seas.ucla.edu

*WEF Member

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• **Abstract**

Secondary settling tanks (SSTs) are a crucial process that determines the performance of the activated sludge process. However, their performance is often far from satisfactory. In the last 30 years, computational fluid dynamics (CFD) has become a robust and cost-efficient tool for designing new SSTs, modifying the geometries of existing SSTs and improved control techniques in wastewater treatment plants. The first part of this review paper discusses the different approaches to model the motion of particles in SSTs. The applications of different multiphase approaches and the widely applied single-phase approach in different SST studies are reviewed. The second part reviews current CFD research and engineering practice, focusing on the formation and the effect of density currents, effects of different design variables, parameter uncertainties in modeling structures, and atmospheric conditions. Finally, challenges and future improvements of sub-models (sludge settling, rheology, turbulence, and flocculation) in the SST model framework are identified.

• **Practitioner points**

- The first journal review for the CFD applications in SSTs over the last decade.
- The controversy over the relationship between SOR and SST performance can be largely explained by the prediction of the CFD model.
- Density decoupling in the turbulence model is possible for well-baffled SSTs.
- The relative importance of three modeling parameters is summarized.
- Recommendations for future data collection are provided.

• **Key words**

computational fluid dynamics; density-driven flow; secondary settling tank; wastewater treatment

Introduction

In conventional wastewater treatment plants (WWTPs), the activated sludge process (ASP) is widely used to remove organic matter and remove nutrients such as nitrogen and phosphorus. The aeration tank effluent is a concentrated slurry and must be separated from the liquid. Gravity sedimentation is the most commonly used treatment method for solids separation in WWTPs and the process used to remove the highly concentrated suspended solids from the bioreactor effluent is a secondary settling tank (SST), also known as a sedimentation tank or a secondary clarifier (Ramin et al., 2014).

There are three crucial parameters describing the performance of an SST: (a) effluent suspended solids (ESS) concentration, (b) returned activated sludge (RAS) concentration, and (c) sludge blanket height (SBH) (1995, 1995). As noted by Kleine and Reddy (2005), there are two different functions of SSTs: clarification and thickening. Clarification is used to separate the suspended solids (SS) from the effluent. Thickening is used to concentrate the sludge for recycle or disposal in a small volume. These two functions are influenced by six interrelated processes in SSTs described by McCorquodale, Motta, Griborio, Homes, and Georgiou (2004): (a) hydrodynamics, (b) sludge settling, (c) sludge rheology, (d) turbulence, (e) flocculation, and (f) heat exchange and temperature changes. Although not related to clarification/thickening, overloaded SSTs are often used to store the biomass inventory during peak flows. In summary, failure in clarification or thickening processes usually results from a poor understanding of these interrelated processes.

Currently, SSTs are designed based on empirical hydraulic criteria, such as surface overflow rate (SOR) (Parker, 1983; Parker et al., 1996; Parker & Stenquist, 1986), and few designers use methods based upon CFD. However, this design procedure assumes that the flow in the SST is ideal and ignores other influential factors in SSTs such as (a) internal geometries; (b) sludge properties; (c) atmospheric conditions, including wind and temperature effects (Stamou, Theodoridis, & Xanthopoulos, 2009). With the increase of computational power and the development of the computational fluid dynamics (CFD) models, which were initially associated with aerospace and mechanical engineering, much interest now exists in the environmental engineering field to understand non-ideal flow in SSTs and other processes. Compared with traditional design approaches, techniques based on CFD are of high precision, allowing evaluation and prediction of SST performance (Karpinska & Bridgeman, 2016).

In the last two decades, CFD has been applied to simulate multiphase flow in wastewater treatment facilities, such as primary settling tanks (PST) (Liu & Garcia, 2011; Patziger, Günthert, Jardin, Kainz, & Londong, 2016), aeration tanks (Karpinska & Bridgeman, 2016, 2018a, 2018b; Rehman, Maere, Vesvikar, Amerlinck, & Nopens, 2014), SSTs (Das et al., 2016; Gao & Stenstrom, 2017; McCorquodale et al., 2004; Patziger, Kainz, Hunze, & Józsa, 2012; Ramalingam et al., 2012; Weiss, Plósz, Essemiani, & Meinhold, 2007; Wicklein & Samstag, 2009; Xanthos, Ramalingam, Lipke, McKenna, & Fillos, 2013), and sludge digestions (Craig, Nieuwoudt, & Niemand, 2013; Kariyama, Zhai, & Wu, 2018). Among these applications, SSTs have been most widely studied. Therefore, CFD-aided modeling is becoming a robust tool for the optimization of existing SSTs and design of new SSTs.

Developments and applications of SST CFD models over the past 30 years can be divided into three main periods:

1. The 1980s to the early 1990s: developing the numerical model under neutral density condition (Abdel-Gawad & McCorquodale, 1984, 1985; Adams & Rodi, 1990; Imam & McCorquodale, 1983; Imam, McCorquodale, & Bewtra, 1983).
2. The late 1980s to early 1990s: developing the numerical model for the density-driven flow (DeVantier & Larock, 1986; DeVantier & Larock, 1987; Zhou & McCorquodale, 1992a, 1992b, 1992c; McCorquodale & Zhou, 1993).
3. The mid-1990s to present: studying different influential factors, optimizing the internal baffling structures of existing SSTs and designing new SSTs (De Clercq, 2003; Krebs, 1995; McCorquodale et al., 2004; Patziger et al., 2012; Vitasovic, Zhou, McCorquodale, & Lingren, 1997; Wicklein et al., 2015).

Before the early 2000s, SST CFD models were limited to two-dimensional (2D) scale because of the limited computational speed of computers. McCorquodale et al. (2004) extended 2D models to a Quasi-3D (Q3D) model and verified the model results with the data from three different treatment plants. Since then, the Quasi-3D model becomes the most widely used CFD tool for SST evaluation (e.g., Chu et al., 2015; Esping, Lfft, & Shaposka, 2015; Griborio & McCorquodale, 2016; Winkler, Kelly, Schauer, & Menniti, 2015). Compared with other early models developed before the 2000s, Q3D is more advanced and predicts accurate results for SSTs with symmetrical geometries. It can generate mesh based on the SST's structures, discretize governing equations and sub-models, and output the simulation results. The sub-models include a settling model with 5 settling regions, a flocculation model, a scraper function, and thermal boundaries which can describe the thermal interactions with the outer environment. However, since the model assumes symmetry in either radial direction for circular SSTs or linear direction for rectangular SSTs, the prediction accuracy decreases as the geometry becomes asymmetrical (Morse, Siczka, & Nielsen, 2016). The inherent 2D model also limits its capacity in predicting swirl flow pattern generated by the energy dissipating inlet (EDI) vanes for circular SSTs and in resolving the corner effects of effluent launders for rectangular SSTs (Xanthos et al., 2013). Also, the model does not couple wind shear effects and should not be used if wind is a major forcing function on the SST hydrodynamics (McCorquodale, Griborio, & Georgiou, 2005).

Due to significant increase in computing power over the last decade, more and more researchers are developing 3D SST models and studying the optimization of the SSTs' performance based on the commercial CFD models (Fan, Xu, Ke, & Shi, 2007; Gong et al., 2011; Ramalingam et al., 2009, 2012; Wang et al., 2008; Xanthos et al., 2011, 2013). In the last decade, commercial CFD solution codes, such as ANSYS FLUENT, have been widely used for 3D SST modeling due to their advantages of easy-learning, friendly interface and stability. Free software, user-coded programs, and open-source codes have been employed in previous studies. A summary of CFD codes used in previous SST CFD studies is presented in Table 1.

In spite of the significant and rapid advances in the development and applications of SST CFD models over the last 30 years, great challenges to create accurate and fast CFD simulations of SSTs still exist. Plósz et al. (2012) in an earlier critical review summarized the advances in SST modeling and indicated important shortcomings, including the poor understanding of solids settling outside the zone settling range and the lack of widely accepted and easy method to measure sludge settling behavior outside the zone settling range.

In this review, the first goal is to review the CFD modeling strategies of SSTs used in engineering practice and academia. The state of current research and engineering practice are next reviewed by categorizing it into four sections: (a) hydrodynamics analysis; (b) effects of primary design variables on SSTs' performance; (c) parameters in modeling structures; and (d)

Table 1. Summary of CFD codes used in previous studies of secondary settling tanks

CATEGORY	CFD CODES	REFERENCES
Commercial software	ANSYS Fluent	Laine et al. (1999), De Clercq (2003), Jayanti and Narayanan (2004), Shaw et al. (2005), Weiss et al. (2007), Fan et al. (2007), Ramalingam et al. (2009), Xanthos et al. (2011), Gong et al. (2011), Patziger et al. (2012), Ramalingam et al. (2012), Tarpagkou & Pantokratoras, (2013), Xanthos et al. (2013), Wicklein and Samstag (2014), Das et al. (2016), Patziger (2016), Gao and Stenstrom (2018a, 2018b, 2019a, 2019b)
	ANSYS CFX	Matko, Fawcett, Sharp, and Stephenson (1996), Mohanarangam and Stephens (2009), Stamou et al. (2009), Burt (2010)
	PHOENICS	Krebs (1991), Dahl et al. (1994), Krebs et al. (1992), Krebs, Vischer, and Gujer (1995), Brouckaert and Buckley (1999)
	STAR-CD	Wang et al. (2008), Wang et al. (2011)
	SettlerSIMs	Narayanan et al. (2002), Samstag et al. (2010), Zhou et al. (2010)
	HACM	Gerges and McCorquodale (2008)
Free software	Quasi-3D	McCorquodale et al. (2004), Winkler et al. (2015), Gao and Stenstrom (2017)
	SettlerCAD	Vitasovic et al. (1997), Ekama and Marais (2004), Wahlberg et al. (1998)
	FAST-2D	Lakehal et al. (1999), Armbruster, Krebs, and Rodi (2001), Saffarian et al. (2010), Saffarian, Hamedi, and Shams (2011)
Open-source code	OpenFOAM	Ramin et al. (2014)
User-coded program	–	Godo and McCorquodale (1991), Zhou and McCorquodale (1992a, 1992b, 1992c), Zhou et al. (1992), Kleine and Reddy (2005)

atmospheric conditions. Finally, challenges in CFD SSTs simulation are identified.

Modeling Strategies Of Sludge Settling Process

The sludge settling process is a multiphase problem in SSTs. The accurate numerical simulation of the sludge settling process relies on the accurate assessment of the sludge transport phenomena and the character of interaction between the phases. Table 2 summarizes the descriptions of different multiphase approaches used in modeling of WWTP processes shown in Karpinska and Bridgeman (2016) and their applications in settling tanks.

Multiphase modeling

Euler–Lagrange model. In the Euler–Lagrange (EL) model, the governing phase (fluid) is treated as a continuum by solving the Navier–Stokes (NS) equations, while the behavior of the dispersed phase (e.g., solids) is solved by tracking a large number of particles through the calculated flow field. The trajectories of particles are predicted by integrating the force balance on a single particle.

The Euler–Lagrange model is often used to evaluate the behavior of individual particles or particles with specific characteristics (Karpinska, 2013). The model allows for one-way coupling where the discrete phase follows the continuous phase flow field or two-way coupling, where the effect of the discrete phase on the continuous phase is included. One-way coupling EL model has been used to model the solids transport in full-scale settling tanks in water treatment plants (WTPs).

Jayanti and Narayanan (2004) applied the one-way EL model to study the effect of flow field on solids distribution in a pilot-scale settling tank. The turbulent flow was modeled by the Reynolds-averaged Navier–Stokes (RANS) equations with the standard k-ε (SKE) turbulence closure. The experimental studies conducted by McCorquodale (1976) and Szalai, Krebs, and Rodi (1994) in a centrally fed settling tank were used to validate the prediction of the flow field for neutrally buoyant flow. The study showed that particles smaller than a lower cut-off size (100 μm in this case) would be difficult to settle while those large than the upper cut-off size (300 μm in this case) would settle easily.

Goula, Kostoglou, Karapantsios, and Zouboulis (2008a) applied a CFD model coupled with the one-way EL model to study the influence of the inlet baffle for a full-scale circular settling tank in a WTP. The turbulent flow was accounted by the shear stress transport k-ω turbulence model. The grid-independent test was performed to eliminate numerical diffusion and to determine the best compromise between simulation accuracy and computational time. The experimental measurements and the simulated values of the floc size distribution in the tank effluent were compared to validate the CFD model. Their study showed that the addition of a vertical baffle at the feed section of the settling tank reduced the effluent solid concentration by 85%. The validated CFD model was further used to assess the effect of a warmer influent on the performance of the settling tank (Goula, Kostoglou, Karapantsios, & Zouboulis, 2008b). The study showed that a temperature difference of only 1°C is sufficient to induce a temperature-driven density current and reduce the detention time as well as the solids removal efficiency.

Tarpagkou and Pantokratoras (2013) used CFD models coupled with the EL model to simulate the 3D hydrodynamics and flow behavior in a settling tank. Unlike most of the previous numerical investigations, the EL model with

Table 2. Summary of multiphase approaches used in settling tanks modeling

MODEL	CONCEPT	MODELING	APPLICATIONS	COMMENTS FOR SETTLING TANK MODELING
Euler–Lagrange	Liquid phase treated with Eulerian approach. Every particle tracked along trajectory	A set of averaged NS equations for the liquid phase. A set of Newton's 2nd law (N2L) equations applied to all particles. Momentum transfer terms in both NS and N2L to be modeled	Jayanti and Narayanan (2004); Goula et al. (2008a), Goula et al. (2008b); Tarpagkou and Pantokratoras (2013)	It does not consider the interparticle interaction and is computational expensive to track a large number of particles (De Clercq, 2003)
Eulerian	Each phase modeled as a separate fluid	A set of averaged, volume fractionated weighted NS equations for each phase. Momentum transfer terms and constitutive equations to be modeled	Fan et al. (2007); Liu and Garcia (2011)	None of the calculated particle concentration field was compared with the observed particle concentration distribution
Mixture	Both phases treated as a single phase	Single set of NS equations. Effective mixture density and viscosity to be modeled	Wicklein and Samstag (2009); Al-Sammarraee, Chan, Salim, & Mahabaleswar, (2009a,b); Liu, Zhang, and Wei (2016)	Unrealistic for most wastewater modeling applications where a wide range of particle diameters exist and change as they flow through a tank (Wicklein & Samstag, 2009)
VOF	Each phase modeled as a separate fluid. The interface between the phases is tracked	Interface tracked via a continuity equation and the domains of the single phases are defined. A set of phase-specific NS equations with momentum exchange terms are solved for each domain	Rostami et al. (2011)	Due to the strong effect of surface wind shown in Gao and Stenstrom (2019d), VOF model can be used to simulate the water surface fluctuation and simulate the effect of surface baffling structures

two-way coupled calculations was applied to identify the influence between the discrete and the continuous phases over a change of particle diameters and volume fractions. The RNG k-ε model was used to describe turbulent flow. The study provided detailed procedures on the application of two-way coupled EL model which are valuable to researchers to learn how to use the EL model. The depth-average velocity magnitude along the radial direction of the tank was compared among three different mesh densities to demonstrate grid-independent values. Next, the prediction of the depth-average velocity magnitude along the radial direction of the tank on the optimal mesh density was compared with experimental measurements.

The study showed that the effect of particles on the fluid phase is higher as the particle size and volume fraction increases.

However, a number of factors such as the effects of density currents, sludge flocculation, and hindered settling were neglected in those studies, and the results were appropriate in water treatment settling tanks but not in SSTs in WWTPs. Currently, the EL model has not been used in a full-scale SST study. The application of the EL model in full-scale SSTs needs extensive interparticle interactions which requires large computational resources (De Clercq, 2003). Karpinska and Bridgeman (2016) stated that the EL model is the most computational expensive multiphase model which limits its popularity in the simulation of WWTPs. Additionally, Burt (2010) stated that the EL model cannot reliably predict solids retention in SSTs which precludes it use in SSTs where the sludge bed deposition and accumulation is a vital element of the hydrodynamics.

Eulerian–Eulerian model. The Eulerian–Eulerian (EE) multiphase model is a multi-fluid model, where both the governing fluid phase and dispersed particle phase are solved using NS equations. The equations for the two phases are coupled by the phase volume fraction and the inter-phase exchange terms are defined as sources or sinks to represent the exchange of mass, momentum, and heat between the two phases (Jayanti & Narayanan, 2004). The sum of volume fraction equals to unity.

In WWTPs, the EE model is often used to model the gas-liquid or solid-liquid flow in aeration systems (Karpinska & Bridgeman, 2016). Currently, there are only a few applications of the EE model in settling tanks. Fan et al. (2007) applied a three-dimensional (3D) CFD model coupled with the EE multiphase model to investigate the hydrodynamics of a circular SST and the impact of the internal baffle. SKE model was used to describe turbulent effects.

However, sludge withdrawal and sludge settling behavior were excluded in this study which makes the CFD prediction results less accurate to describe the SST's actual behavior. Also, the flow and concentration fields were not compared with experimental data. Therefore, the reliability of prediction results by the EE multiphase model in this study is unknown.

Liu and Garcia (2011) applied a 3D CFD model coupled with the EE model to evaluate the hydrodynamics and identify the optimal internal structures for a PST. The SKE model with Bingham plastic model is used to simulate the turbulence and the sludge rheological behavior. Hindered settling was described via the double exponential settling equation (Takács, Patry, & Nolasco, 1991). While the prediction of velocity field showed good agreements with the experimental data, the concentration field data were not calibrated with the experimental data. Therefore, the performance of the EE model on the prediction of the sludge concentration is unclear. Therefore, the further application of the EE model in settling tanks in WWTPs needs to calibrate the prediction of sludge concentration profiles with field data in order to demonstrate the model reliability. Additionally, in modeling the particle settling process, due to heavy computational effort, only a limited number of particle size classes can be considered, which is another limitation to the application of EE model for a full-scale SST.

Mixture model. The mixture model is a simplified multiphase model. The interfacial relationships in the multiphase model are eliminated by using only one momentum equation for the complex mixture (De Clercq, 2003). The algebraic equations are used to solve relative velocities to describe the dispersed phases.

The mixture model has been applied to simulate gas-liquid turbulent flow in bioreactors (Yang et al., 2011), solid-liquid turbulent flow for setting tanks in WTPs (Al-Sammarraee et al., 2009a, 2009b), and for SSTs in WWTPs (Liu et al., 2016).

Al-Sammarraee, Chan, Salim, and Mahabaleswar (2009a) compared the performance of the large eddy simulation (LES) model with the SKE model for a full-scale 3D longitudinal settling tank in a WTP. The mixture multiphase model was used to model the particle sedimentation process. Five different mesh grids were used to determine the best compromise between accuracy and computational cost. The prediction of effluent concentration of particle with different sizes showed good agreement with experimental measurements. The study showed that the SKE model in general has similar performance in predicting velocity, turbulence, and particle settling efficiencies in the bulk part of the settling tank, while LES can more accurately resolve the small-scale flow patterns near the inlet, effluent weir, and tank bottom. The authors further applied their model to investigate the influence of baffles on the particle sedimentation process (Al-Sammarraee, Chan, Salim, & Mahabaleswar, 2009b). Four different baffle numbers (zero, two, three, and four baffles) were compared. The study concluded that increase in the the number of baffles causes larger suppression of the horizontal velocities and improves the particle settling.

Liu et al. (2016) applied the mixture multiphase model with the SKE turbulence model to quantitatively investigate the effect of a baffle on the hydrodynamics and solids removal efficiency for an SST. However, since the prediction results were not validated with experimental data, the prediction accuracy of the model for the SST is unknown.

In order to understand the performance of mixture multiphase model in predicting a full-scale SST in the WWTP, Wicklein and Samstag (2009) compared its prediction of solids concentration profiles with field measurements in both rectangular and circular SSTs. The results showed that the prediction of the mixture model was poor in predicting the sludge concentration distribution. The authors explained that a wide range of particle diameters exist (Khelifa & Hill, 2006) and change as they flow through an SST as a result of which a single representative input particle size cannot be easily determined for the mixture model.

Volume of Fluid (VOF) model. The VOF model is designed to track the location and motion of a free surface between immiscible fluids. While the phases are immiscible, the fields for all variables and properties are shared and represented by volume-averaged values.

Karpinska and Bridgeman (2016) noted that this model can be used to model stratified and free-surface flows, filling, sloshing, and motion of large bubbles (slug flow). However, it is very rare to find the application of the VOF model in settling tanks modeling studies. Rostami, Shahrokhi, Said, and Syafalni (2011) applied the VOF model to study the effect of the free surface in a PST. They compared the velocity distribution predicted by the VOF method and confined surface with experimental results and showed that the VOF method predicted more accurate velocity field than the confined surface method. However, the flow was treated as pure water without particles; therefore, the effect of the particles on the velocity distribution was neglected. An application of the VOF model was recommended by Gao and Stenstrom (2019c, 2019d) in their surface wind effect on the performance of both circular and rectangular SSTs. The VOF model has advantages to study how the surface baffling structures influence the surface wind.

Single-phase modeling

Although sludge settling is a multiphase problem, a single-phase flow model has become the most widely applied approach in the academic (e.g. De Clercq, 2003; Lakehal, Krebs, Krijgsman, & Rodi, 1999; Patziger et al., 2012; Ramin et al., 2014; Saffarian, Hamedi, & Shams, 2010; Vitasovic et al., 1997; Weiss et al., 2007) and non-academic SST projects (e.g., Morse et al., 2016; Shaw, McGuffie, Wallis-Lage, & Barnard, 2005; Wicklein & Samstag, 2014) because of its economy and accuracy for the prediction of sludge distribution. Additionally, Wicklein and Samstag (2009) quantitatively compared the performance of this single-phase modeling approach with the mixture multiphase model in both full-scale circular and rectangular SSTs. Their results showed that this single-phase modeling approach outperforms multiphase models in predicting the sludge concentration distribution in both rectangular and circular SSTs.

This approach assumes the solids follow the advective flow by coupling a separate solids transport equation (Nopens et al., 2012). Also, additional equations related with density state and the sludge settling velocity (usually the settling function of Vesilind (1968) or the Takács et al. (1991)) need to be included to achieve this coupling. The sludge transport equation, density state equation, and Takács settling function are shown in Patziger et al. (2012).

The single-phase modeling approach, due to its accuracy and modest need for computing resources, has become the most popular approach for CFD SST modeling. In the next section, we review the applications of CFD SST models and how they are improving SST design and operation.

Applications of CFD Modeling Research And Engineering Practice

In the last two decades, multiple applications of CFD models to existing SSTs have been made. These applications include: (a) studying the underflow hydromechanics, such as the occurrence and effects of density currents; (b) studying the primary design variables on the performance of SSTs (tank loadings, tank geometry, and sludge management); and (c) studying the variation of ambient environmental factors (temperature and wind).

Underflow hydromechanics (turbulent flow and buoyancy effects)

Since the influent to the SST is a high concentration of mixed liquor suspended solids (MLSS), the flow in SSTs is driven by density. However, since the causes of density currents were controversial (Taebi-harandy & Schroeder, 2000), many early CFD research studies from 1990s to early 2000s focused on the study of the density currents (Gerges & McCorquodale, 2000; Godo & McCorquodale, 1991; Lyn, Stamou, & Rodi, 1992; McCorquodale et al., 2004; Moursi, McCorquodale, & El-Sebakhy, 1995; Vitasovic et al., 1997). Moursi et al. (1995) suggested that the density currents (bottom or surface) may occur from the temperature difference, concentration effects, and the release of gas bubbles. Also, Gerges and McCorquodale (2000) concluded that there were two types of thermal density currents in SSTs: (a) heat exchange between water surface and the surroundings and (b) temperature variance between the influent and ambient water. Both effects may occur at the same time. Godo and McCorquodale (1991) studied the effect of the temperature difference between influent and effluent on the formation of density currents in a lab-scale rectangular settling tank and concluded that a temperature difference, as small as 0.2°C, could result in the formation of density currents.

McCorquodale et al. (2004) conducted the most thorough numerical study on the formation of density currents (surface and bottom) and their effects on the SST performance. The numerical studies were tested on different influent temperature variations, surface heat exchange, and on two MLSS concentrations (300 and 2,800 mg/L). The lower MLSS was used to simulate the loading condition in PSTs. McCorquodale et al.'s (2004) findings on the formation of the density currents and their effects on PSTs and SSTs are summarized in Table 3.

For the case of low suspended solids concentration, corresponding to a PST, warmer influent temperatures tend to create surface density currents, which is consistent with the Taebi-harandy and Schroeder's (2000) observations in a lab-scale SST. McCorquodale et al. (2004) showed that surface density currents form in PSTs with warmer influent and bottom density currents form with cooler influent. This indicates that the temperature-induced buoyant effect is stronger than the gravitational effect caused by the low concentration of MLSS. Also, the performance of PSTs deteriorates with temperature variations. Therefore, the temperature is the dominant factor affecting the performance of PSTs and the type of density currents produced.

Table 3 also shows that only bottom density currents form in SSTs, which indicates that the gravitational effect caused by the high concentration of MLSS is stronger than the temperature-induced buoyancy effect. Therefore, MLSS concentration is the dominant factor in producing density currents (surface or bottom), with or without the consideration of temperature effects (Gao & Stenstrom, 2017; Krebs, Stamou, García-Heras, & Rodi, 1996; Lyn et al., 1992; McCorquodale et al., 2004; Zhou & McCorquodale, 1992b, 1992c; Zhou, McCorquodale, & Vitasovic, 1992).

Some researchers have suggested that density currents cause a negative effect on the SSTs' performance by reducing their volume usage efficiency (Lyn et al., 1992; Vitasovic et al., 1997). However, Table 3 indicates that the performance of SSTs under different influent temperatures and surface heat exchange is different. The cooler inflow and surface heating reduce the performance of SSTs by increasing the upflow velocities and vertical mixing close to the side wall, which increases the ESS. Warmer inflow and surface cooling tend to have the opposite effect by reducing upflow velocities and mixing. McCorquodale et al.'s (2004) numerical results are consistent with the Wells and LaLiberte's (1998) field observations of three different SSTs during the winter.

Table 3. Formation of the density current and its effect on PSTs and SSTs (McCorquodale et al., 2004)

	DENSITY CURRENT TYPE		PERFORMANCE	
	MLSS (300 MG/L)	MLSS (2,800 MG/L)	MLSS (300 MG/L)	MLSS (2,800 MG/L)
Cooler inflow	Bottom	Bottom	Decrease	Decrease
Warmer inflow	Surface	Bottom	Decrease	Increase
Surface cooling	Not shown	Bottom	Decrease	Increase
Surface heating	Not shown	Bottom	Decrease	Decrease

Samstag, McCorquodale, and Zhou (1992), although ignoring temperature change and heat exchange, indicated that stable density stratification in the settling and effluent zone contributed to significant damping of vertical mixing, concluding that concentration-induced density currents do not reduce ESS removal efficiency. An exception occurs where there is a sudden increase of the inlet MLSS concentration, which increases the upward currents near the side wall, changing the flow pattern. These observations and numerical results show that influent temperature variations, surface heat exchange, and MLSS concentrations are all major factors affecting the performance of SSTs.

Effects of primary design variables on the performance of SSTs

The Clarifier Research Technical Committee (CRTC) recommended a comprehensive protocol for analysis of the hydraulic efficiency of SSTs (Wahlberg, Keinath, & Parker, 1994). In the CRTC study, the following aspects of SSTs were considered (Vitasovic et al., 1997):

1. Tank loading, including hydraulic and solids loading and RAS flow rate.
2. Tank geometry, including radius and depths, size of the flocculating well, bottom slope, sludge removal mechanisms, and launder arrangements.
3. Sludge settling characteristics.

Effects of hydraulics and sludge loading. The effects of hydraulics and sludge loading rates (SLR) on the performance of SSTs have been studied and debated based on the observations by different researchers from different WWTPs in the last three decades. These observations have not been extensively analyzed in previous CFD studies, and are discussed in this review. A particularly controversial finding is the relationship between SOR, SST depth, and performance.

Parker (1983) indicated that the ESS concentration is usually assumed to directly relate to SOR. The results of his field measurements showed an obvious effect of high SOR on ESS. Therefore, he recommended a lower SOR from 1.7 m/h to 1.4 m/h (1,003 to 826 gallons/ft^2-day) to improve effluent quality. However, field measurements conducted by Wahlberg, Peterson, Flancher, Johnson, and Lynch (1993) did not find a significant influence of SOR on ESS. Similarly, Parker et al. (1996) studied the performance of flocculator-SSTs in several different WWTPs. The combined experience suggests that the performance of SSTs is stable over a very broad range in overflow rates.

Parker, Kinnear, and Wahlberg (2001) compared the operating performances of SSTs in three different studies (Okuno & Fukuda, 1992; Parker & Stenquist, 1986; Stahl & Chen, 1996) and showed that deep SSTs, no matter circular or rectangular, were more stable than shallow SSTs, over a wide range of SORs. For shallower units, the poor SOR performance may relate to the higher sludge blanket. This problem can be mitigated by building deeper SSTs or changing operating conditions to increase separation between the sludge blanket and the effluent weirs (Ekama et al., 1997). Therefore, Parker et al. (2001) concluded that the existence of a correlation between SOR and ESS indicates either a design problem or poor operation. Vestner and Günthert (2004) investigated four operating parameters: SOR, sludge volume loading rate, MLSS, and flocculation time in two SSTs. They concluded that at appropriate loading, the influence of SOR and SLR on ESS is very small, and it is important to consider the effect of inlet MLSS concentration and flocculation time.

To explain the contradictory results of the effects of SOR on ESS observed at different WWTPs, we summarized the relationship between ESS and SOR in Figure 1 from ten different SSTs. In order to simplify the figure, raw data points from the first eight studies are not shown and best fit lines are shown instead. Three sets of data points from three SSTs and their best fits from our previous studies (Gao & Stenstrom, 2017, 2019b) are also shown in Figure 1. It shows that three sets of observations and predictions from three of our previous studies indicate the ESS increases with the increase of SOR, while five other sets of observations show a relatively constant ESS over a large range of SORs. These five sets of observations are for deeper SSTs, ranging from 4.3 m to 5.5 m SSTs. The observations showing an increasing relationship between ESS and SOR are all for shallow SSTs ranging from 1.8 m to 3.3 m except for Gao and Stenstrom (2017), which is 4.1 m deep. The dependence of ESS on SOR may be related to depth, with deeper SSTs performing much better. This should be a topic for future research.

In order to compare the performance of an SST with different SWDs without other geometric differences, the modified Witney SST studied in Burt (2010) and Gao and Stenstrom (2019b) was simulated with different SWDs. Burt (2010) measured r_h in a series of batch settling tests. An SVI corresponding to the measured r_h was calculated as 110 using the Daigger (1995) correlation, which indicates a good settling sludge. The original SWD was 1.8 m and was simulated over a range 0.8 m, 2.8 m, 3.8 m, and 4.8 m. Figure 2 shows the prediction of ESS, RAS, and SBH as the variation of SWD.

It shows that the ESS increases from 12.5 to 33.1 mg/L as the SWD increases from 0.8 to 2.8 m and then decreases from 33.1 to 10 mg/L as the SWD increases from 2.8 to 4.8 m. These are puzzling results but can be explained by the density currents shown in Figure 3a-2-e-2. At the shallowest depth, 0.8 m shown in Figure 3a-2, the density current impacts the SST floor and is deflected away from the effluent weir, creating a more quiescent condition. As the SST depth is increased, the density current does not impact the floor and travels to the effluent weir. At much greater depth, the density current still flows to the effluent weir but is well below the weir and does not disturb the quiescent conditions. This set of results shows the complexity of SST dynamics and is perhaps a reason why there is so much controversy over the importance of SST depth and the need for more research.

The variation of the RAS concentration is negligible and the SBH from the water surface increases as the increase of

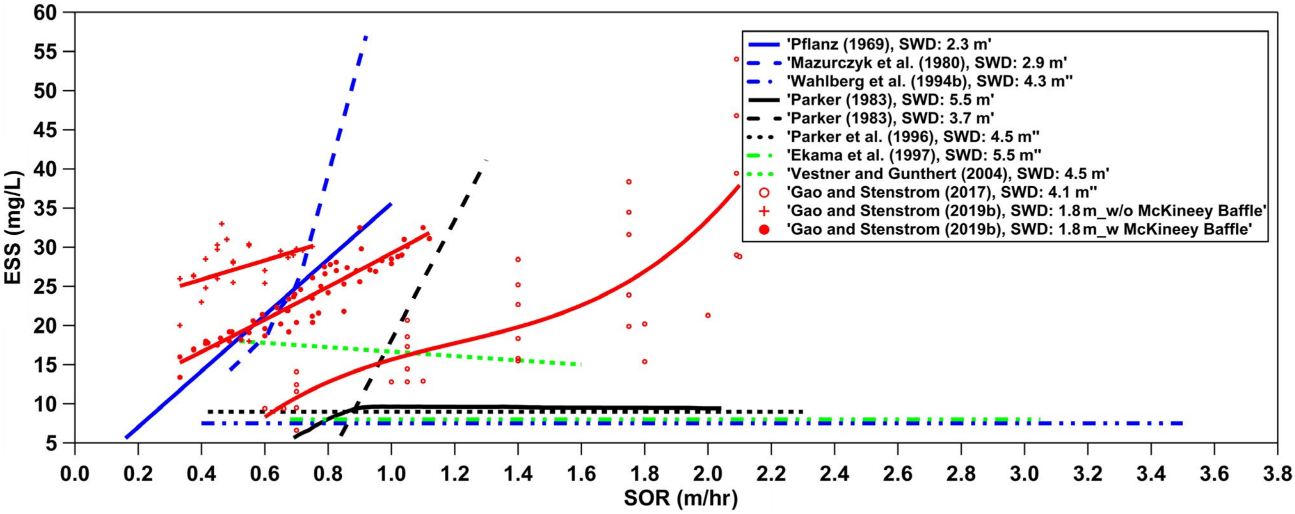

Figure 1. Relationship between SOR and ESS.

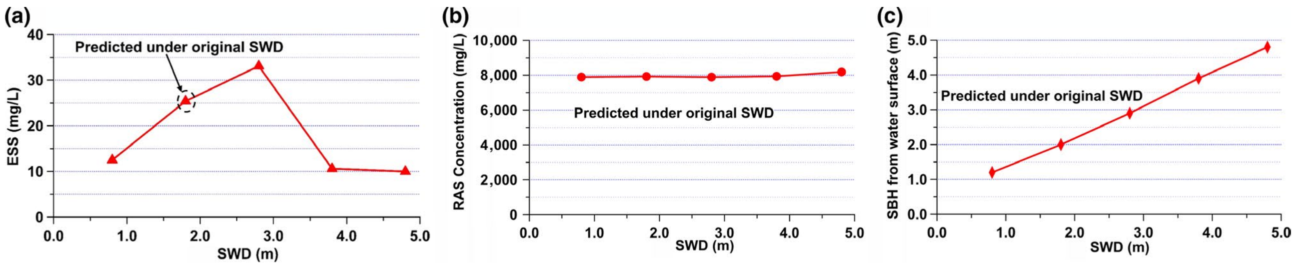

Figure 2. Variation of SWD (m) on the performance of modified Witney SST (SBH is 850 mg/L contour followed by Burt (2010), the depth of the Witney SST at the center is 6.15 m, the original SWD of Witney SST is 1.8 m).

SWD from 0.8 to 4.8 m. Figure 3 shows the concentration and velocity profiles of the modified Witney SST as SWD is increased. It shows that when the SDW is only 0.8 m, currents from the inlet zone flow directly to the sludge blanket without the formation of density currents. The sludge blanket dissipates the flow energy coming from the inlet zone. Therefore, the upward velocity to the effluent weir is weak and the ESS is very low. However, as the SDW increases from 0.8 to 2.8 m, sludge blanket is below the McKinney baffle, and the density current flows across the top of the sludge blanket level scouring particles to the effluent weir along the side wall. As the SWD is further increased, density currents do not have enough energy to rise to the level of the effluent weirs, and the ESS decreases. Gao and Stenstrom (2017) simulations at 4.1 m SWD showed a trend of increasing ESS with SOR, similar to the shallow SSTs. This case has poor sludge settling properties (SVI = 280, calculated from Daigger's (1995) correlation) making the SBH higher, which impacted the density currents and allowed particles to be transported to the effluent. The simulation results are supported by Ekama et al.'s (1997) observations.

The overall conclusion of these simulations is that while the McKinney baffle improves SST performance and increases its flow capacity, if a density current is produced at the same height as the top of the sludge blanket, the current can scour particles into the effluent. For very shallow SSTs, density currents may impact the middle or lower part of sludge blanket, dissipating the velocity. For deep SSTs, density currents never reach the height of the effluent weirs. These simulations showed that ESS is not a simple function of SOR and that different geometries can complicate the results.

The simulations support the conclusion that deeper SSTs are able to produce the highest quality effluent. First of all, it can separate the ESS from the highly concentrated sludge at the bottom with larger distance. Also, more energy of density currents can be dissipated when density currents turning to flow upward along deeper side wall to the effluent weir. Therefore, the effect of density currents can be reduced. The deeper SSTs also have greater capacity to store sludge which can be important when treating peak flows.

Additionally, Vitasovic et al. (1997) used a 2D CFD model to study the relationship between SOR/SLR and ESS. In their study, the RAS ratio and MLSS were kept constant, while SLR increased with SOR. The study showed that the ESS is more sensitive to the change of SOR than the change of SLR. Wahlberg, Gerges, Gharagozian, and Stenstrom (1998) followed Vitasovic et al.'s study and used the same CFD model to further evaluate the relationship between SOR/SLR and ESS. In their study, 24 simulations were summarized in two simulation matrices. In Matrix 1, simulations 1 through 16 were divided into four groups. The four groups have four different SLRs, but within each group the SLR is constant. The change of ESS can be observed with the increase of SOR and decrease of RAS ratio in each group in Matrix 1. In Matrix 2, simulations 17–24 were divided into two groups of data. Different from Matrix 1, the two groups in Matrix 2 have different SORs, rather than SLRs, and they are constant in each group. The change of ESS can be observed with the increase of SLR and increase of RAS ratio in each group in the Matrix 2. Their study showed that the ESS is more sensitive to the change of SLR than the change of SOR, which is opposite to the results of Vitasovic et al. (1997).

Gao and Stenstrom (2017) followed the studies of Vitasovic et al. (1997) and Wahlberg et al. (1998). In their study, the Q3D model was used to not only reproduce all the simulations in these two previous studies, but added two more groups in Wahlberg et al.'s Matrix 2. All the operation parameters, such as SOR, RAS ratio, MLSS, and SLR, were changed in the same way as used in Vitasovic et al. (1997) and Wahlberg et al. (1998). Their predictions were consistent with the prediction results of Vitasovic et al. (1997) and opposite to the results of Wahlberg et al. (1998). They concluded that ESS is always more sensitive to SOR than SLR, no matter which operating parameters are manipulated using Vitasovic et al.'s or Wahlberg et al.'s methods.

The controversy over traditional design parameters such as SOR and SLR is of continuing interest among CFD researchers and has resulted in an increased used of CFD models by practical engineers. A number of CFD modeling case studies have been presented at the Water Environment Federation's Annual Technical Exhibition and Conference (WEFTEC) (Chu et al., 2015; Esping et al., 2015; Griborio & McCorquodale, 2016; Griborio et al., 2010; Winkler et al., 2015).

Safety factor of state point analysis (SPA). The prediction of the CFD model can be used to estimate the safety factor of the prediction of state point analysis (SPA). State point analysis is one of the most practical methods to evaluate the performance of existing SSTs and to improve the operation of full-scale SSTs (Water Environmental Federation, 2006). However, since it simplifies SSTs to the idealized steady-state one-dimensional (1D) model, it ignores the non-ideal effects of SST hydrodynamics and the arrangement of the internal baffling structures (Ekama & Marais, 2004). Therefore, the actual capacities of SSTs are lower than the prediction of the SPA and the application of the SPA without a proper safety factor can cause incorrect operation of the SST.

Ekama and Marais (2004) and McCorquodale et al. (2004) were the pioneer studies estimating the safety factor of the SPA with the CFD model. Ekama and Marais (2004) applied the SettlerCAD and increased the SLR and SOR by increasing the flow rate while keeping the returned flow rate and inlet MLSS constant. Their study showed that 20% was a reasonable estimation to the safety factor.

McCorquodale et al. (2004) used their 2Dc model and estimated the safety factor in two different stress testing methods: (a) increasing the SLR and SOR by increasing the flow rate, while keeping the RAS ratio and inlet MLSS constant; (b) increasing the SLR by increasing the MLSS, while keeping the inflow rate and returned flow rate constant. Their study showed that the 20% was an accurate safety factor (designing at only 80% of predicted capacity by SPA) when adjusting the operation parameters using the 1st stress testing method, while it underpredicted the SST real capacity when adjusting the operation parameters using the 2nd stress testing method.

Because the different conclusions made in these two studies could be caused by the application of different stress testing methods, geometries of SSTs, sludge settling properties, and CFD programs, Gao and Stenstrom (2019b) studied the safety factor using these three different stress testing methods in the same SSTs with the same sludge settling properties using CFD. In their study, the Fluent-based 2D SST model was used to study the safety factor in SSTs with different internal baffling structures. The study showed that both internal baffling structures and stress testing methods influenced the estimation of the safety factor of the SPA. The safety factor ranged from 20% to 64% for the original SST under different stress testing methods, while it ranged from 15% to 57% for the modified SST. Therefore, Gao and Stenstrom (2019b) concluded that 20% is not conservative enough for all SSTs and evaluating the safety factor of the SPA should be tested on a case-by-case basis.

Tank geometry and construction features. After Zhou and McCorquodale (1992a) overcame the local numerical instabilities near the reaction baffle lip and successfully simulated the entire flow domain from inlet zone to effluent weirs in an SST, SST CFD models have been widely applied to study the effect of geometric features (dimensions and internal baffling structures) and to optimize the geometry. The structural optimization for the inlet zone includes optimizing the location and submergence of the inlet baffle (a cylinder surrounding the feed zone for circular SSTs, or a wall across the width of rectangular SSTs, either solid or porous). These inlet baffles have since become known as EDI. An influent floor baffle (McKinney baffle) if located below inlet structure and flocculating well, if present, can (a) dissipate the strong inflow energy, (b) reduce recirculation and avoid the re-entrainment of already clarified liquid into the inlet zone, and (c) avoid the scouring on the thickened sludge at the bottom of the SST. The structure optimization for the outlet zone includes optimizing the arrangement (length and location) of the outlet weirs and adding various baffles on the side wall, especially Stamford baffle, to reduce the upward flow to the effluent weir. Table 4 summarizes previous CFD studies of SST geometry features. Figure 4 shows different SST geometry features.

1. The structure optimization for the inlet zone

Imam et al. (1983) indicated that a solid, cylindrical inlet baffle, enclosing the inflow zone, can be used to dissipate the kinetic energy of the inlet flow and to stabilize the flow. They studied the effect of baffle submergence on the solids removal and found that the removal rate increased at a specific range of baffle submergence. However, because of the limitation of their model, they could solve only the hydrodynamics of

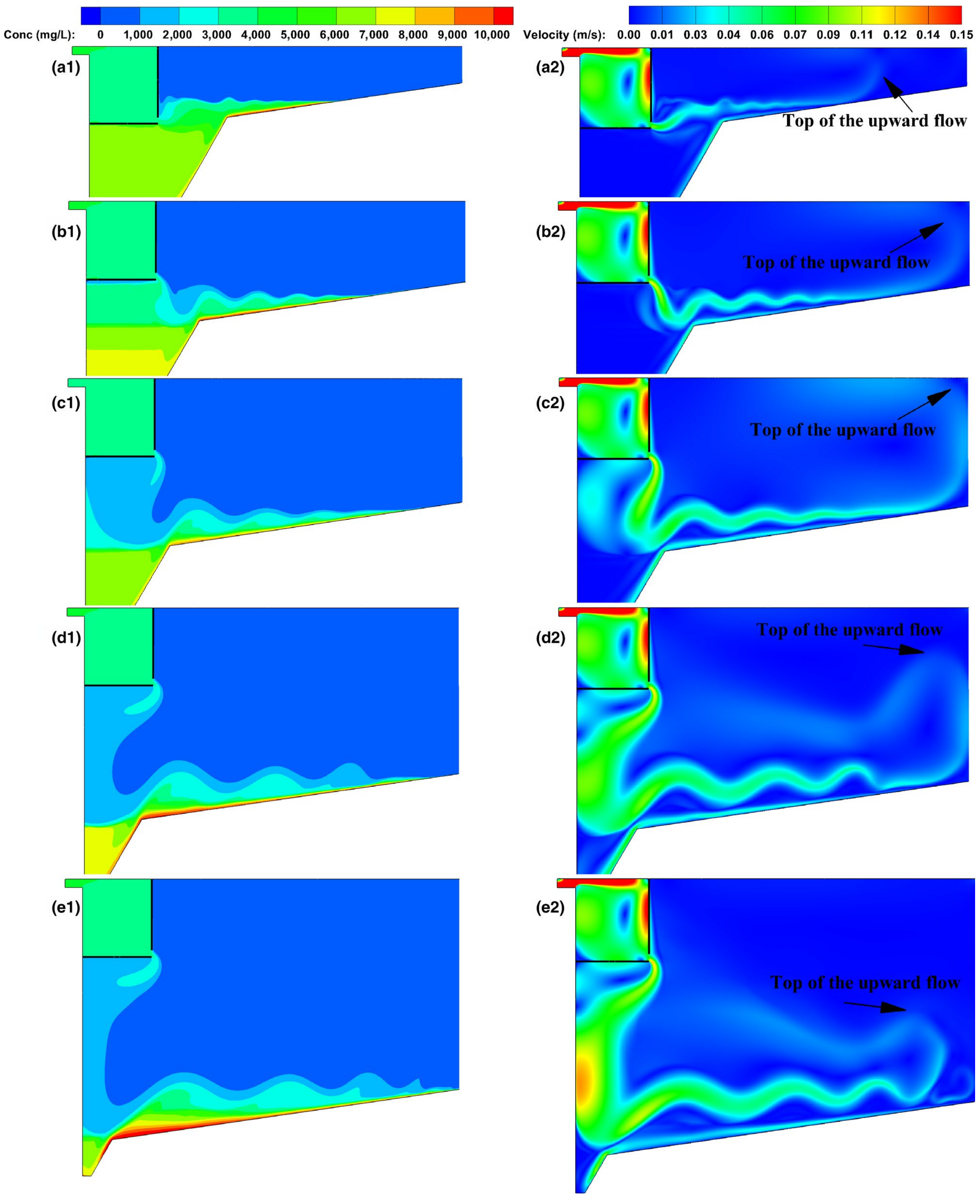

Figure 3. Concentration (left) and velocity (right) profiles for the modified Witney SST with different SWD values (SWD = 0.8, 1.8, 2.8, 3.8, and 4.8 m for profiles (a) to (e), respectively).

Table 4. Configuration optimizations in previous studies

	REFERENCES	BAFFLE TYPES	SCALE	DIM.	MODEL	VALIDATION	REMARKS
Inlet structures	Krebs (1991)	Inlet solid baffle	Pilot	2D	RANS+ constant eddy viscosity	N/A	Optimized the inlet baffle location
	Zhou et al. (1992)	Inlet solid baffle	Full	2D	URANS+ *sk-ε*	Velocity	Inlet baffle improved SST performance
	Wang et al. (2011)	Inlet solid baffle	Full	3D	URANS+ *sk-ε*	Velocity	Optimized the baffle depth and location
	Patziger et al. (2012)	Inlet solid baffle	Full	2D	URANS+ *sk-ε*	Velocity/ concentration	Optimized the inlet position and transient sludge control
	Patziger (2016)	Inlet solid baffle	Full	2D	URANS+ *sk-ε*	Velocity/ concentration	Optimized the inlet position; length of the radial circulation; upward velocities at the side wall
	Krebs et al. (1992))	Porous wall	Pilot	2D	RANS+ constant eddy viscosity	N/A	Simulated porous walls with various porosity fraction
	Xanthos et al. (2011)	Porous wall	Full	3D	URANS+ *sk-ε*	N/A	Perforated baffle reduced flow recirculation
	Vitasovic et al. (1997)	Flocculation well	Full	2D	URANS+ *sk-ε*	ESS	Optimized the flocculating well size
	Narayanan et al. (2002)	EDI	Full	3D	URANS+ *sk-ε*	N/A	SST without an EDI bottom performed better
	Ghawi and Kris (2011)	EDI	Full	3D	URANS+ *sk-ε*	N/A	LA-EDI improved SST performance
	Burt (2010)	McKinney baffle	Full	2D	URANS+ *sk-w*	Concentration and velocity	McKinney baffle reduced ESS
	Gao and Stenstrom (2019b)	McKinney baffle	Full	2D	URANS+ *sk-ε*	Concentration and velocity	McKinney baffle increased the SST capacity
Outlet structures	Gerges and McCorquodale (2008)	Stamford baffle	Full	2D	URANS+ mixing length model	N/A	60° version of the Stamford baffle could be more effective than a typical 45° baffle
	Xanthos et al. (2013)	Effluent weirs	Full	3D	URANS+ *sk-ε*	ESS	Optimized effluent weir locations
	Wicklein and Samstag (2014)	Surface lamella plates	Full	2D/3D	URANS+ *k-ε*	N/A	Lamella plates did not show any benefit

(Continues)

Table 4. (Continued)

	REFERENCES	BAFFLE TYPES	SCALE	DIM.	MODEL	VALIDATION	REMARKS
Comprehensive evaluations	Shaw et al. (2005)	Inlet geometries (tangential EDI; LA EDI; concentric plates; no EDI)	Full	3D	URANS+ RNG *k*-*ε*	N/A	EDI provided the best performance at high flows
	Zhou et al. (2010)	EDI, flocculating well	Full	3D	URANS+ *sk*-*ε*	Field data	Comprehensive evaluation of SST inlet geometries
	Samstag et al. (2010)	EDI, flocculating well	Full	3D	URANS+ *sk*-*ε*	Velocity and concentration	Comprehensive evaluation of SST inlet geometries
	Das et al. (2016)	Inlet geometries (inward baffle; EDI; submerged skirt; no EDI)	Full	3D	URANS+ Realizable *k*-*ε*	N/A	Inward baffle was added
	Chu et al. (2015)	Inlet baffle; flocculating well; Stamford baffle	Full	2D	URANS+ mixing length model	ESS	Comprehensive evaluation of SST inlet geometries
	Winkler et al. (2015)	Inlet baffle; flocculating well; Stamford baffle; effluent weir location	Full	2D	URANS+ mixing length model	SBH	Comprehensive evaluation of different SST geometries

a rectangular settling tank operating under neutral density conditions. Zhou and McCorquodale (1992b) and Zhou et al. (1992) applied a 2D unsteady-state model to study the effect of a solid inlet baffle under the density-driven flow and showed that the baffle reduced the entrainment compensating flow and improved the tank performance. Wang et al. (2011) applied a 3D unsteady-state model to optimize the optimal baffling location and length. Patziger et al. (2016) applied a Fluent-based 2D unsteady-state model to optimize the inlet structure of an SST in the Graz Municipal WWTP and to investigate the correlation between the length of the radial density current and the upward velocities at the side wall of the SST. The results showed that the optimized inlet structure can reduce the density jet length by 18% and decrease the ESS by 70% under wet weather conditions.

In addition to the study of a solid baffle for the inlet zone, CFD models have also been used to study a perforated inlet baffle. A porous baffle can not only dissipate the inlet energy, reducing the density waterfall, but also can enhance flocculation (Krebs, Vischer, & Gujer, 1992). Kawamura (1981) was the pioneer in studying perforated baffle in the sedimentation process. His study indicated that hole shapes, porosity fractions, and numbers of porous walls are the three main influential factors to the performance of a porous wall. Krebs et al. (1992) applied a 2D steady-state model to study porous baffles with various porosity fraction for a pilot SST. The most significant contribution from this study was that their study provided a design guidance to the application of porous walls. However, the sludge was modeled by a non-flocculent, clay suspension in their research and the effect of the porous wall on the flocculation enhancement cannot be verified. Baumer, Volkart, and Krebs (1996) followed Krebs et al.'s (1992) research and compared the effect of a solid and perforated baffle with different porosity on the performance of a pilot SST under dynamic loadings. The results showed that the perforated baffle performed better than the solid baffle under dynamic loading conditions, which can be helpful to maintain the stable performance of the SST during the wet weather. However, because of limited computational capacity, previous CFD researchers could only study the effect of perforated baffles on a 2D scale model and simplified orifice distributions and shapes to several horizontal slots. For the perforated baffle which cannot be easily simplified into a wall with several horizontal slots, a 3D model should be applied to improve the prediction accuracy of

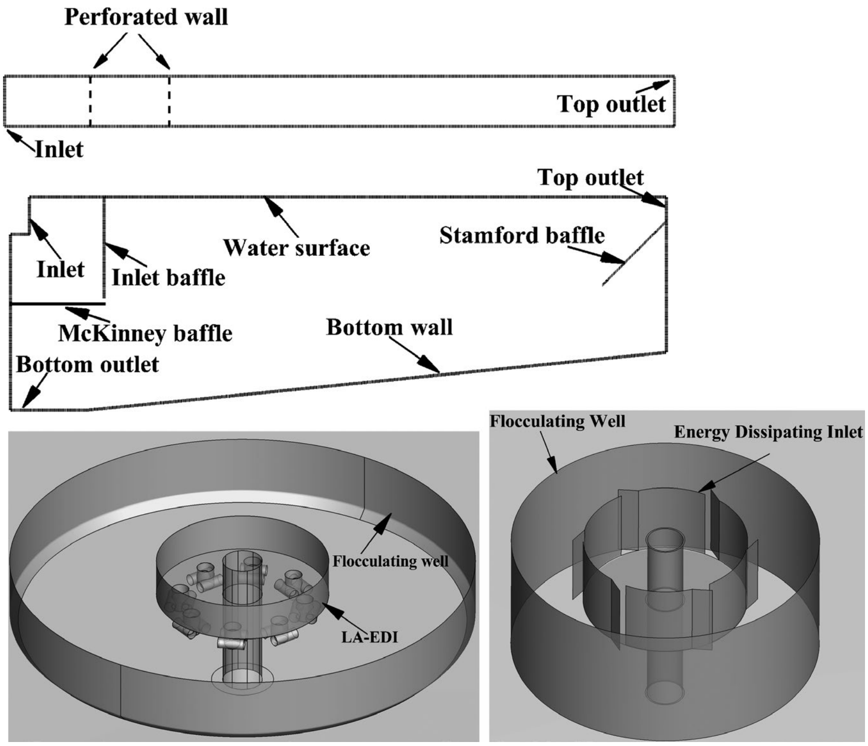

Figure 4. SST geometry features (a: perforated wall in a rectangular SST; b: inlet baffle, McKinney baffle and 45° Stamford baffle in a circular SST; c: LA-EDI and flocculating well in a circular SST; d: tangential EDI and flocculating well in a circular SST).

the perforated baffle with various porosity fractions and orifice distribution. Zhou, Vitasovic, and McCorquodale (1997) conducted a comprehensive modification for the SST in the Passaic Valley Sewerage Commission, including the addition of a perforated wall with two different porosities. A 3D unsteady-state model was used to predict ESS in CFD stress tests. The predicted results showed the modified SST with the perforated wall reduced the ESS by at least 20%. Ramalingam et al. (2009) and Xanthos et al. (2011) applied a 3D unsteady-state model to optimize the performance of an SST with a perforated wall in New York City water pollution control plants and was especially concerned with performance during periods of poor settling and peak flow conditions. The perforated baffle reduced flow recirculation into the inlet zone and provided plug flow pattern immediately after the baffle, which promotes effluent quality.

Burt and Ganeshalingam (2005) were the first to study the effect of an inlet floor baffle or McKinney baffle. The addition of a McKinney baffle placed below the inlet circular baffle separates the inlet zone from the settling zone and sludge thickening zone. They found that the baffle reduces the re-entrainment of already clarified liquid into the inlet baffle and avoids density currents impinging the thickened sludge blanket. It can also reduce the fluctuation of ESS during dynamic hydraulic loading. Burt (2010) optimized the inlet of the SST at the Witney sewage treatment works in Oxfordshire with the addition of a McKinney baffle. Gao and Stenstrom (2019b) conducted a series of CFD stress tests on the original Witney SST without McKinney baffle and on the new SST with the addition of the McKinney baffle. Their simulation results showed that the flow capacity in the new SST can be approximately 1.4–2 times the capacity of the old SST.

More effective EDIs evolved from inlet baffles to improve the SST performance and much of the recent SST design and development work has focused on the installation and modification of the EDIs (Shaw et al., 2005). The EDI can confine the high turbulent energy and spread the load uniformly near the top of the flocculating well. The most common EDI has tangential outlets which can generate a swirling flow pattern. However, Burt and Ganeshalingam (2005) indicated that the combination of slot size and vane angle can produce excessive swirl and cause resuspension of the sludge below the flocculating well. Therefore, they suggested that the size of the slot and the vane angle should generate strong momentum in the flocculating well to improve sludge flocculation, but not too strong to produce sludge resuspension. Narayanan et al. (2002) conducted side-by-side full-scale hydraulic testing and hydrodynamic modeling of SSTs at the Laguna Subregional Water Reclamation Facility of the City of Santa Rosa. Their CFD model confirmed the results obtained in field work that the SST without the tangential EDI bottom has significantly higher capacity at peak flows. Shaw et al. (2005) applied a 3D transient model to compare the performance of four different inlet geometries (Tangential EDI; LA EDI; Concentric plates EDI; no EDI). They indicated that the poor performance of the tangential EDI can also be improved by breaking up the spiral motion by the inclusion of baffles within the flocculating well. Their comparison showed that these four different inlet geometries performed similarly at low flows and that the

LA EDI provided the best performance at high flows. Ghawi and Kris (2011) showed that the LA-EDI can maintain high removal efficiency even when the sludge has a poor settling ability (SVI > 200 ml/g). Zhou et al. (2010) applied a 3D transient model to upgrade an existing SST in Tai Po Sewage Treatment Plant, Hong Kong. The existing tangential EDI was replaced by an innovative "multilayer energy dissipating inlet column" (MEDIC, US Patent No. 7378027). Perforated concentric circular baffles sufficiently dissipated the inflow energy and distributed the influent flow jets along the vertical and tangential direction before entering the flocculating well. After comprehensive field-testing and CFD modeling evaluation (Samstag, Zhou, Chan, Royer, & Brown, 2010), the MEDIC EDI was also recommended for North San Mateo County Sanitation District wastewater treatment plant.

In order to improve the usage of the entire flocculating well, Vitasovic et al. (1997) simulated reducing the size of the flocculating well from 46% to 28% of the tank diameter. The simulations showed that the smaller well reduced the ESS from 87 mg/L to 15 mg/L. Parker et al. (1996), based on plant-scale observations, concluded that the optimum size of the flocculating well to produce lowest ESS is between 32% and 35% of SST radius. Burt and Ganeshalingam (2005) using simulations found that a flocculating well radius of 20% SST radius and half the SST depth produced the lowest ESS.

2. The structure optimization of the effluent weirs and Stamford Baffle

The outlet optimization includes optimizing the arrangement (length and location) of the outlet weirs and adding various baffles on the side wall, especially the Stamford baffle. Krebs et al. (1996) developed a 2D model for a rectangular SST using three different lengths (short, medium, long) to compare different effluent weir positions. The first weir position was at the end of the tank and perpendicular to the tank length. The other position was a single launder, parallel to the tank length, and located at varying distances from the end, based on the overall tank length. The study showed that the weir greatly affected performance position with weirs in the middle of the SST being best. The perpendicular weir at the end of the SST tended to produce a bottom current at the end wall.

Zhou et al. (1997) in their study of rectangular SSTs proposed eight longitudinal effluent weirs to replace the six surrounding effluent launders (two on each side and two perpendicular toward the effluent end of the SST). The total length of the new launders was 33% longer than the original launders. Xanthos et al. (2013) followed Zhou et al. (1997)'s study and simulated the SST with both 2D and 3D transient models. The 3D model results were more illustrative of the impacts and were able to show that concentration contours along weir width.

For circular SSTs, the 2D simulations have shown the effects various baffles, such as the Stamford baffle at the side wall to reduce ESS. Burt and Ganeshalingam (2005) listed five different types of baffles, but only the Stamford baffle was studied in their numerical model. Their simulation results showed that the effluent flow bypasses the Stamford baffle in shallow SSTs, which limits its influence in shallow SSTs. The Stamford baffle predicted to perform better in SSTs with deeper sidewall depths and flat bottoms. Gerges and McCorquodale (2008) indicated that the 60-degree down angel version of the Stamford baffle could be more effective than the standard 45-degree Stamford baffle.

Sludge settling characteristics. Sludge settling properties are one of the major processes impacting the performance of an SST. Based on the sludge concentration and particle or floc interactions, sludge settling can be described in four different zones: (a) discrete; (b) flocculent; (c) hindered or zone; and (d) compression (Kynch, 1952). De Clercq (2003) and McCorquodale et al. (2004) reviewed the development of sludge settling models based on these four zones. Also, Li and Stenstrom (2014) critically reviewed the development of 1D SST models, including the advantage and disadvantage of various settling behaviors, the numerical techniques required to solve the 1D model, and the important 1D modeling challenges. Therefore, this review includes the impacts of the settling velocity sub-model on 2D and 3D CFD simulations, but does not discuss the mathematics of the 1D settling equations.

There are a number of settling velocity functions and Li and Stenstrom (2014) reviewed 15 of them, but the Takács et al. (1991) (Equation 1) and the Vesilind (1968) (Equation 2) are the most widely applied sub-models coupled in SST CFD models. Some recent developments of sludge settling models are based on these two models (e.g., Daigger, Redmond, & Downing, 2018; Guo, Zhang, Xu, & Chen, 2009; Ramin et al., 2014).

$$V_s = V_o \left(e^{-r_h (C - C_{\min})} - e^{-r_p (C - C_{\min})} \right) \quad (1)$$

$$V_s = V_o e^{-r_h C} \quad (2)$$

The first exponential term in the Takács settling model is the same as the Vesilind model, which is used to describe the sludge settling in the hindered settling zone, while the addition of the second exponential term is used to describe the slow and non-settling discrete particles (Ekama & Marais, 2004). Different sludge settling characteristics directly determine the coefficient (r_h) in the first exponential term, which can be obtained from a series of batch tests over a concentration range, by measuring the zone settling velocities as the linear descending rate of the liquid/solid interface (Ramin et al., 2014). However, the calibration procedure requires a series of time-consuming batch tests; therefore, it is often used for research but seldom used in field investigations (Burt, 2010; De Clercq, 2003; McCorquodale et al., 2004; Ramin et al., 2014). An alternative method which is widely used in field and consulting projects (e.g. Chu et al., 2015; Esping et al., 2015; Griborio & McCorquodale, 2016; Winkler et al., 2015) is to correlate r_h with easily measurable parameters in WWTPs (Daigger et al., 2018), including SVI, stirred sludge volume index (SSVI), and diluted sludge volume index (DSVI).

Also, there were some recent studies that considered power-law functions instead of Veslind and Takács's exponential equations to analyze hindered settling (Bürger, Careaga, & Diehl, 2017; Diehl, Zambrano, & Carlsson, 2015; Torfs et al., 2017; Valle Medina & Laurent, 2020). In Medina and Laurent's study, they used Bürger–Diehl's transport equation (Bürger, Diehl, Farås, Nopens, & Torfs, 2013) to model the sludge settling behavior in a batch settling column and in a full-scale SST. The sludge compression was coupled in the model and was described by a separate second-order dispersion term. The predicted batch settling curves by the settling models with and without the compression were compared with the experimental data. The results showed that the sludge settling model with compression provided more accurate prediction in 1D sludge settling tests. However, the performance of the sludge settling model with and without the compression was not compared with the field data of the SST. Therefore, this sludge-hindered compression model could be an alternative approach to simulate sludge settling once it is validated in an SST with the observed velocity and concentration profiles as well as with the performance indicators, such as ESS, SBH, and RAS.

There have also been efforts to develop the settling velocity from fundamental analysis of force action on activated sludge. Xu, Yin, Xu, and Yu (2017) developed a force-based mechanistic model for the standard EE multiphase model. Compared with the standard EE multiphase model, he developed new equations for modeling the drag force, solids pressure, and shear stress. The prediction results were validated by the experimental data from their own tests and from De Clercq, Nopens, Defrancq, and Vanrolleghem (2008) and Ramin et al. (2014). The results demonstrated that this mechanistic model can be directly executed in CFD software. Therefore, this force-based model can be another alternative approach to simulate the sludge settling.

Parameters in modeling structures

Although CFD models have been applied to study SSTs in the last three decades, there are some uncertainties of model parameters and only three recent papers (Gao & Stenstrom, 2018b, 2019a, 2019e) studied the uncertainty of these parameters on the performance of SSTs. These model parameters are (a) generation of turbulent kinetic energy (TKE) due to buoyancy (G_b) in the TKE equation of the k-ε family turbulence models; (b) buoyancy coefficient (C_3) in the turbulent dissipation rate (TDR) equation of the k-ε family turbulence models; (c) turbulent Schmidt number (σ_c) in the sludge transport equation; (d) the coefficient in the second exponential term of the Takács settling equation (r_p); and (e) dry solids density (ρ_p). Table 5 shows the values of C_3, σ_c, r_p, and ρ_p used in previous studies. These parameters are coupled in the sludge transport equation, density state equation, and Takács settling equation shown in previous section and the turbulence model shown below:

For simplicity, only the standard k-ε turbulence (SKE) model is shown here:

$$\rho \frac{\partial k}{\partial t} + \rho \nabla \left(\overrightarrow{u_i} k \right) = \rho \nabla \left[\left(\nu + \frac{\nu_t}{\sigma_k} \right) \nabla k \right] + G_k + G_b - \rho \varepsilon \quad (3)$$

$$\rho \frac{\partial k}{\partial t} + \rho \nabla \left(\overrightarrow{u_i} \varepsilon \right) = \rho \nabla \left[\left(\nu + \frac{\nu_t}{\sigma_\varepsilon} \right) \nabla \varepsilon \right] + C_1 \frac{\varepsilon}{k} \left(G_k - C_3 G_b \right) - C_2 \rho \frac{\varepsilon^2}{k} \quad (4)$$

G_k represents the generation of TKE due to the mean velocity gradients, and G_b corresponds to the generation of TKE due to buoyancy. The dimensionless empirical constants are given the standard values suggested by Rodi (1993), $C_\mu = 0.09$, $C_1 = 1.44$, $C_2 = 1.92$, $\sigma_k = 1.0$, and $\sigma_\varepsilon = 1.3$.

Generation of TKE due to buoyancy (G_b). Many early CFD SST studies ignored the G_b in the TKE equation of the turbulence model. For example, DeVantier and Larock (1986, 1987) ignored the G_b due to the convergence difficulty in modeling the flow with a high MLSS concentration and the limited computational resources. Zhou and McCorquodale (1992a, 1992b) used the G_b-decoupled SKE model to study the hydrodynamics of SSTs. However, simulated MLSS in the study was only 1,400 mg/L. Vitasovic et al. (1997) studied the effect of SOR and the internal baffling structure of the SST with a 2D CFD model. The buoyancy term was also ignored in their SKE model. The latest CFD SST model decoupling the buoyancy term in the turbulence model was in Tamayol, Firoozabadi, and Ahmadi (2010). In this study, the effects of Reynolds number and Froude number on the optimal baffle location and the flow field were studied. However, the study did not show the calibration of their CFD prediction results with experimental data; therefore, the reliability of their model results is unknown.

More recent CFD SST studies coupled G_b in the turbulence model (Lakehal et al., 1999; Ramalingam et al., 2012; Ramin et al., 2014; Shahrokhi, Rostami, Said, Yazdi, & Syafalni, 2013; Xanthos et al., 2011). However, none has simulated the same cases with and without G_b coupling. Therefore, Gao and Stenstrom (2018b, 2019a) studied the need for coupling the G_b by simulating same cases with and without coupling G_b.

Gao and Stenstrom (2018b) used a Fluent-based 2D SST model to study the effects of G_b at Darvill SST reported by McCorquodale et al. (2004). The inlet baffling structure of the Darvill SST is very poor and has only a center well. The effect of the G_b was analyzed under different MLSS concentrations and sludge settling properties. The study showed that the G_b should be coupled in the TKE equation to correctly predict the Darvill SST performance, unless both MLSS is very low and sludge settling is very high.

In order to generalize the effects of baffling structures on the buoyancy-induced turbulence in SSTs, the authors used eleven SST geometries, including four circular SSTs and seven rectangular SSTs in their further study (Gao & Stenstrom, 2019a). The results show that the G_b has strong impacts on the prediction of the performance of an SST with similar poor baffling structures to the Darvill SST. For an SST with good baffling structures, the prediction of G_b-decoupled and G_b-coupled turbulence model is similar. Therefore, G_b is a buoyancy correction term to correctly predict the performance of an SST with poor baffling structures.

Table 5. Ranges of parameters in modeling structures in previous studies

NO.	PARAMETERS IN MODELING: TURBULENT SCHMIDT NUMBER Σ_Y	Σ_R	REFERENCES
1	0.5	0.5	Stamou, Adams, and Rodi (1989)
2	0.7	0.7	
3	1.0	1.0	
4	1.0	0.5	Zhou and McCorquodale (1992a)
5	1.0	1.0	Zhou and McCorquodale (1992c)
6	0.5	1.0	
7	1.0	1.0	Dahl (1993)
8	0.7	0.7	Lakehal et al. (1999)
9	0.5–0.9	0.7	Saffarian et al. (2010)
10	1.0	1.0	Ramin et al. (2014)

NO.	COEFFICIENT OF BUOYANCY TERM (C_3)	REFERENCES
1	0.15	Ramin et al. (2014)
2	0.2	Dahl (1993); Shahrokhi et al. (2013)
3	0–0.2	Lakehal et al. (1999); Saffarian et al. (2010)
4	0.8	Xanthos et al. (2011)

NO.	R_P (L/G)	REFERENCES
1	4	McCorquodale et al. (2004)
2	5	McCorquodale et al. (2004)
3	10	Ekama and Marais (2004); Vitasovic et al. (1997)
4	$10r_h$[a]	Ekama et al. (1997); Weiss et al. (2007)
5	15–30	Zhou and McCorquodale (1992a)
6	20	Tamayol, Firoozabadi, and Ahmadi (2008)

NO.	P_P (KG/M^3)	REFERENCES
1	1,100	Deininger, Holthausen, and Wilderer (1998)
2	1,450	Larsen (1977); Lakehal et al. (1999)
3	1,500	Tarpagkou and Pantokratoras (2013)
4	1,600	Weiss et al. (2007)
5	1,360–1,660	Zhou and McCorquodale (1992a)
6	1,700–1,800	Kinnear (2002)
7	1,907/1,743/2,070	Xu et al. (2017)

Note. [a]r_h: the coefficient in the first exponential term of the Takács settling equation.

Buoyancy coefficient (C_3) and turbulent Schmidt number (σ_c). The application of C_3 in the TDR equation and σ_c in the sludge transport equation has varied widely among different studies. Gao and Stenstrom (2018b) showed that among the performance indicators (ESS, SBH, RAS concentration), none of them is sensitive to the change of C_3 and only SBH is sensitive to the variation of the σ_c. Therefore, C_3 can be removed from the TDR equation to improve the rate of convergence and reduce computing time and σ_c can be used to adjust SBH, when ESS and RAS are well calibrated to the field data.

Coefficient r_p in the Takács settling equation and dry solids density (ρ_p). Ekama and Marais (2004) noted that the value of r_p in the Takács settling equation affects the CFD prediction of ESS. Also, since ρ_p is coupled in every governing equation, different values of ρ_p may influence CFD prediction of the entire SST hydrodynamics. As shown in Table 5, there is a large range of values of these two parameters. Gao and Stenstrom (2019e) studied the influence of these two parameters under varied flow conditions. The results showed that ESS is very sensitive to the change of r_p. The incorrect specification of r_p may predict clarification failure of the SST when the field measurements indicate the SST performs well. Also, the incorrect value of r_p may show that the clarification performance in the original SST outperforms the modified SST, which is opposite to the field measurements. However, the prediction of SBH and RAS concentration is not sensitive to the r_p; therefore, r_p can be used to adjust ESS, when RAS and SBH are well calibrated to the field data.

Dry solids density (ρ_p) also only affects the prediction of clarification and has little effect on sludge thickening.

However, the effect is smaller than the effect of r_p. Gao and Stenstrom (2019e) indicated that the CFD model still predicts reasonable ESS compared to field data, even after doubling the ρ_p; therefore, the medium value of ρ_p (1,450 kg/m^3) is a good assumption.

Atmospheric conditions

Atmospheric conditions, including ambient and water temperature, and surface wind, are one of the influential factors on an SST performance (McCorquodale et al., 2004). While the effect of temperature on the performance of SSTs has been studied with CFD models in the last 30 years, few studies show the effect of surface wind. Several recent CFD researchers studied the surface wind effect on rectangular settling tanks in WTPs (Gkesouli, Nitsa, Stamou, Rutschmann, & Bui, 2016; Gkesouli & Stamou, 2018; Goodarzi, Lari, & Alighardashi, 2017; Khezri, Biati, & Erfani, 2012; Stamou & Gkesouli, 2015). However, the applicability of these studies to SSTs in WWTPs is limited due to (a) the structural difference between SSTs in WWTPs and settling tanks in WTPs, (b) different solids settling processes, and (c) different solids concentration. Therefore, Gao and Stenstrom (2019c, 2019d) studied the effect of surface wind on the performance of 3D circular and rectangular SSTs, respectively, under different flow conditions. Under each flow condition, the surface wind was simulated in different flow directions and surface wind velocities. The results showed that the surface wind has strong negative impacts on the performance of both rectangular and circular SSTs, especially on circular SSTs. These results have not been verified by field studies but provide significant incentive to perform such studies.

Gao and Stenstrom (2019c) showed that the predicted ESS can double in the circular SST between normal and windy conditions. Also, for the circular SST, surface wind along the inlet port direction resulted in much higher ESS than the surface wind at 45° to the inlet direction. The difference of the predicted ESS between these two surface wind directions increases as the increase of the surface wind speed. For the rectangular SST (Gao & Stenstrom, 2019d), the CFD prediction showed that the counter-current wind has strongest negative impacts on the SST, while the surface wind flowing perpendicular to the SST longitudinal direction has the least negative impacts.

Challenges in CFD SSTs Simulation

Despite the successes of CFD modeling of SSTs in the last 30 years, a significant shortcoming of the CFD modeling is the lack of a generally accepted SST modeling framework (assumptions for sludge settling, sludge rheology, turbulence, and flocculation). The different assumptions implemented for these sub-models in the SST model framework still do not fully satisfy the experimental observations and need further improvements.

Sludge settling model

The development of an advanced sludge settling sub-model can improve the prediction of particle sedimentation in water and wastewater treatment processes. Plósz et al. (2012) provided a critical review of SST modeling techniques to identify recent developments and limitations. They noted that the lack of practical measurement technique for measuring sludge settling behavior outside the hindered settling range is the most important factor that limits the use of advanced settling models. Although advanced techniques such as radiotracing (De Clercq et al., 2008; Vanrolleghem et al., 2006) have been used to obtain high-resolution concentration and compression pressure profiles during batch settling tests, high complexity and cost may prohibit their use as a routine test method (Li & Stenstrom, 2014).

Plósz et al. (2012) also noted that the poor understanding of solids settling outside the zone settling range limits the development of the settling model. Firstly, the lack of understanding of transition behavior from zone settling into compression settling limits the accuracy in predicting observed transient settling interface height. Also, the challenge in observing interface height change in batch tests at low initial concentration (≤500 mg/L) makes it difficult to develop a reliable flocculation velocity model (Li & Stenstrom, 2014). Therefore, although some advanced settling models have been developed based on the Takács settling equation (Equation 1), none of these advanced settling models provides sufficient confidence to make it a widely accepted engineering tool.

Because of these limitations, Vesilind (1968) and Takács et al.'s (1991) settling sub-models are still the most widely applied settling models. As described in previous section, practitioners normally use SVI-based correlation equation to obtain settling parameter, r_h. Giokas, Daigger, Sperling, Kim, and Paraskevas (2003) summarized eight different SVI correlations and two different SSVI correlations. Kelly, Jimenez, Klein, and Merlo (2009) compared the predictions of maximum flow capacity in five different WWTPs by using three different SVI-based correlations (Daigger, 1995; Ozinsky & Ekama, 1995; Wahlberg & Keinath, 1988) with field observations. Figure 5 indicates that the differences between the prediction of SVI-based correlation equations and field observations can be remarkable. For example, for the first WWTP, the prediction of Ozinsky/Ekama correlation was twice as much as the flow capacity in the field observation. In contrast, the Wahlberg/Keinath correlation under-predicted the capacity of the second WWTP by 15%. Therefore, Kelly et al. (2009) concluded that significant care must be given when using these SVI correlations to predict the maximum flow capacity.

However, the relation between SVI and compression settling is unclear and there is no practical method to identify sludge compression characteristic from the SVI (Li & Stenstrom, 2014). From general principles of fluid mechanics, one can derive that compression (stress transmitted between particles), in addition to a hindered settling term (depending on concentration only), has another nonlinear term depending both on concentration and the gradient of the concentration. (An analogy is a nonlinear diffusion or heat equation obtained with Fick's law.) This leads to a second-order spatial

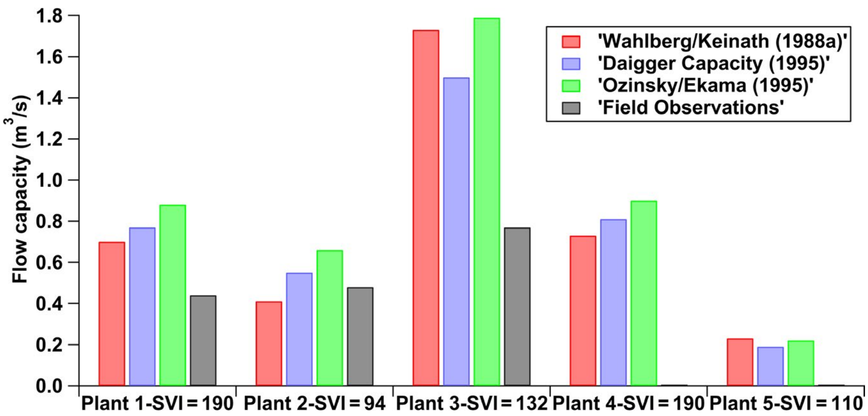

Figure 5. Comparison of flow capacities (m^3/s) based on different SVI-based correlations to field observations in five different WWTPs (adapted from Kelly et al., 2009).

derivative term in the partial differential equation (Auzerais, Jackson, & Russel, 1988; Bürger, Diehl, & Nopens, 2011). The second-order term has a smoothing effect on the solution when the concentration is larger than the so-called critical concentration or gel point above which the particles are in contact.

Guo et al. (2009) indicated that advanced settling models were often developed for the 1D modeling purpose and were limited to static or quasi-static conditions. However, the flow hydrodynamics of settling tanks in 2D or 3D scale is not static and the flow turbulence influences sludge settling. Therefore, Guo et al. (2009) developed a settling model based on the Vesilind equation which relates both sludge concentration and turbulent intensity. Also, Guyonvarch, Ramin, Kulahci, and Plósz (2015) developed a settling model to describe the effect of inflow conditions and design boundary conditions. The prediction results of the CFD model were used as numerical experiments for 1D model identification to degenerate the CFD model into a computationally lighter 1D model. It is important to further develop and implement settling models that describe the sludge behavior across the entire concentration range with measurable parameters.

Sludge rheological model

Sludge rheology directly influences the SST hydrodynamics and the transport of sludge at the bottom of the sludge blanket to the sludge hopper. Since turbulence damping by buoyancy occurs in the sludge blanket of an SST, the sludge viscosity becomes equal to or larger than the turbulence eddy viscosity; therefore, the influence of the sludge viscosity on flow and concentration fields cannot be ignored and an appropriate rheological model should be coupled in the CFD model (De Clercq, 2003). However, there were only a few CFD SST studies that focused on the effect of sludge rheology (Burt, 2010; Dahl, Larsen, & Petersen, 1994; De Clercq, 2003; Lakehal et al., 1999; Saffarian et al., 2010; Weiss et al., 2007), and previous inclusions of rheological model were chosen based on the simplicity of the model or because a particular model fit the observed results. Table 6 summarizes the applications of different sludge rheological models in previous CFD SST studies.

Over the last 30 years, three reviewers (Eshtiaghi, Markis, Yap, Baudez, & Slatter, 2013; Ratkovich et al., 2013; Seyssiecq, Ferrasse, & Roche, 2003) have summarized sludge rheology research progress. Seyssiecq et al. (2003) reviewed the application of rheology in wastewater treatment processes and the rheological characterization of wastewater treatment sludge, such as shear-thinning, viscoplastic, thixotropy, and viscoelasticity behaviors. Eshtiaghi et al. (2013) extended Seyssiec's study and reviewed the commonly used rheometers and different rheological properties of wastewater municipal sludge as well as the effect of concentration, temperature, and water content on these properties. Ratkovich et al. (2013) summarized the different forms of correlation relationships between the combinations of MLSS, shear rate, and temperature with viscosity and compared the measurement protocol from 42 different experimental setups. Their review showed that there was no consensus on the measurement protocol and only a few authors illustrated their measurement protocol sufficiently. As a result, it seems impossible to compare the reliability of the apparent viscosity data published by different research groups which use different rheometers, sludge, and measurement procedures.

Therefore, a systematic and repeatable measurement protocol needs to be defined to improve data reliability. Then a proper rheological model should be developed in order to describe the physical process rather than to fit a qualitative model by means of parameter calibration.

Turbulence model

Table 7 summarizes the description of turbulence models commonly used for Reynold Averaged Navier-Stokes (RANS) closure (Bridgeman, Jefferson, & Parsons, 2009). Although the SKE model has been widely applied in the CFD SST modeling over the last 30 years, Das et al. (2016) noted that it performs poorly for complex flows with strong streamline curvature. Therefore, two modified versions of the SKE model (Realizable k-ε and RNG k-ε models) have been developed and applied in recent sedimentation studies. Additionally, Burt (2010) applied the low Reynold number k-ω turbulence model to study the performance of SSTs.

Table 6. Applications of different sludge rheological models in previous CFD SST studies

BOKIL–BEWTRA MODEL (BOKIL, 1972)	CASSON MODEL	BINGHAM PLASTIC MODEL	HERSCHEL–BULKLEY MODEL	MODIFIED HERSCHEL--BULKLEY MODEL
Lakehal et al. (1999)	Weiss, Plósz, Essemiani, and Meinhold (2006), Weiss et al. (2007)	Dahl et al. (1994)	Dahl (1993)	De Clercq (2003)
Armbruster et al. (2001)	Saffarian et al. (2010)	Lakehal et al. (1999)	Saffarian et al. (2010)	Saffarian et al. (2010)
McCorquodale et al. (2004)		Armbruster et al. (2001)	Ramin et al. (2014)	
Xanthos et al. (2011)		Weiss et al. (2006)	Wagner, Ramin, Szabo, Dechesne, and Plósz (2015)	
Ramalingam et al. (2012)		Saffarian et al. (2010), Saffarian et al. (2011)		
Das et al. (2016)				

However, to the best of the authors knowledge, the RNG k-ε model was only applied in the studies of settling tanks either in drinking water treatment or PSTs in wastewater treatment (Das et al., 2016; Laine, Phan, Pellarin, & Robert, 1999; Patziger & Kiss, 2015; Tamayol et al., 2008; Tarpagkou & Pantokratoras, 2013), where the particle concentration is low, and its buoyancy effect can be ignored and no study applied shear stress transport and Reynolds stress models in the SST modeling. Only Das et al. (2016) applied the Realizable k-ε model to optimize the complex inlet structure of an SST. However, the study did not show the model calibration with the field data to show the superiority of the Realizable k-ε model. Also, only Burt (2010) applied the low Reynold number k-ω turbulence model to the prediction of SSTs and showed good agreement with field observation.

Because of the limitation of the SKE model and the recent application of the more advanced Realizable k-ε and RNG k-ε turbulence models, Gao and Stenstrom (2018a) compared them in predicting the performance of SSTs. Figure 6 shows the adapted prediction of the flow and concentration pattern among these three turbulence models. The results showed that the predictions of flow and sludge concentration fields are remarkably different inside the inlet zone of the SST. The significant different prediction among different turbulence models inside the inlet zone causes more than 10% difference in predicting the RAS concentration and SBH, which can greatly influence the operation of sludge recycle. Also, different turbulence models have a strong influence on the prediction of SST flow capacity. The Realizable k-ε model predicts more than 30% higher flow capacity than the SKE model.

In order to quantitatively evaluate the performance of these turbulence models, the error calculation method used below is similar to the method proposed by Wu (2011):

$$\delta_{\mathrm{ESS}} = \left|\frac{\mathrm{ESS}_P - \mathrm{ESS}_m}{\mathrm{ESS}_m}\right| \times 100\% \tag{5}$$

$$\delta_{\mathrm{RAS}} = \left|\frac{\mathrm{RAS}_P - \mathrm{RAS}_m}{\mathrm{RAS}_m}\right| \times 100\% \tag{6}$$

$$\delta_{\mathrm{SBH}} = \left|\frac{\mathrm{SBH}_P - \mathrm{SBH}_m}{\mathrm{SBH}_m}\right| \times 100\% \tag{7}$$

$$\delta = \mathrm{Ave}\left(\delta_{\mathrm{ESS}} + \delta_{\mathrm{RAS}} + \delta_{\mathrm{SBH}}\right) \tag{8}$$

where δ_{ESS}, δ_{RAS}, and δ_{SBH} are errors for predicted ESS, RAS, and SBH, respectively. ESS_P, RAS_P, and SBH_P are the predicted values. ESS_m, RAS_m, and SBH_m are the measured values. δ is the weighted mean error for the Darvill and Witney SST with respect to the turbulence model where the ESS, RAS, and SBH are assumed to have equal weights. The results are shown in Table 8. It shows that the RNG has solutions with lowest errors than SKE and Realizable k-ε models.

Because this method assumes ESS, RAS, and SBH have equal weights, a more accurate method to compare the accuracy of these turbulence models is to compare the prediction of velocity and concentration inside the inlet zone.

Although the comparison among different turbulence models showed a significant prediction difference inside the inlet zone, previous SST CFD researchers rarely showed the velocity and concentration measurements in this area. Therefore, more data are required in this area for model calibration and turbulence model selection.

Flocculation model

Karpinska and Bridgeman (2016) noted that although the effect of flocculation on the performance of SSTs and the causes which promote flocculation in SSTs have been widely acknowledged, its application in SST modeling is still scarce and limited to a very few examples.

Lyn et al. (1992) coupled the flocculation model in their CFD SST studies. They concluded that the shear-induced flocculation is relatively unimportant to the flow conditions with low MLSS concentrations. However, because of limited computational resources, floc breakup was not modeled, and only MLSS in a very low concentration (80 mg/L) was considered.

Table 7. Comparison of turbulence models used in WWTP modeling (adapted from Bridgeman et al. (2009))

TURBULENCE MODELS	COMMENTS	ADVANTAGES	DISADVANTAGES
Standard k-ε (SKE)	• Semi-empirical modeling of k and ε • Valid for full turbulence only	• Simplest model • Excellent performance for many flows • Well established	• Poor performance in some scenarios (rotating flows, flow separation, adverse pressure gradients) • Assumes isotropy in turbulence • Poor prediction of lateral expansion in three-dimensional wall jets
Renormalized group (RNG) k-ε	• Based on statistical methods, not observed fluid behavior • Effects of small-scale turbulence represented by means of a random forcing function in N-S equations • Similar in form to SKE, but modified dissipation equation to describe high-strain flows better • Differential equation solved for turbulent viscosity, better for transitional flows	• Improved performance for swirling flow compared to the SKE model	• Less stable than the SKE model
Realizable k-ε	• A new eddy-viscosity formula involving a variable C_μ • A new dissipation equation based on dynamic equation of the mean-square vorticity fluctuation	• Suited to round jets, swirling flows, and flow separation	• Not recommended for use with multiple reference frames
Standard k-ω	• $\omega = \varepsilon/k$ = specific dissipation rate • SKE solves for dissipation of k, Standard k-ω solves for rate at which dissipation occurs • Resolves near wall without wall functions, so can be applied through boundary layer	• Valid throughout the boundary layer, subject to sufficiently fine grid resolution	• Separation is typically predicted to be excessive and early
Shear Stress Transport (SST) k-ω	• As k-ω except for gradual change from k-ω in inner region of boundary layer to high Re version of SKE in outer part • Modified turbulent viscosity formulation to account for transport effects of turbulent shear stress	• Suitable for adverse pressure gradients and pressure-induced separation • Accounts for the transport of the principal turbulent shear stress	• Less suitable for free shear flows
Reynolds Stress Model (RSM)	• The most general of all models	• Accurate calculation of mean flow properties and all Reynolds stresses • Yields superior results to k-ε models for flows with stagnation points	• Computationally expensive • Not always more accurate than two-equation models • Harder to obtain converged results

McCorquodale et al. (2004) used the differential equation (Equation 9) described by Parker, Kaufman, and Jenkins (1970), Parker, Kaufman, and Jenkins (1971) to develop their flocculation model. The CFD results showed that this flocculation model accurately predicted flocculation in SSTs. In the last decade, the flocculation model developed in McCorquodale et al. (2004) was applied in several three-dimensional SST studies (Gong et al., 2011; Ramalingam et al., 2012; Xanthos et al., 2011, 2013). Gong et al. (2011) conducted the jar test to compute the coefficients (K_A, K_B) under the MLSS concentrations in the range of 1,400–1,600 mg/L and in the range of the discrete particle settling (160–440 mg/L). The results showed that both K_A and K_B are dependent on the velocity gradient (G) and are different at different MLSS concentrations, which indicates that Equation 9 requires to be further refinement. Therefore, they modified the Equation 9) without considering the dependence of MLSS concentration on K_B. The results in Gong et al. (2011) and Ramalingam et al. (2012) showed that the K_A and K_B in the modified flocculation model (Equation 10) are independent of the MLSS concentration and fits observations better. In the future, the reliability of this modified flocculation model should be

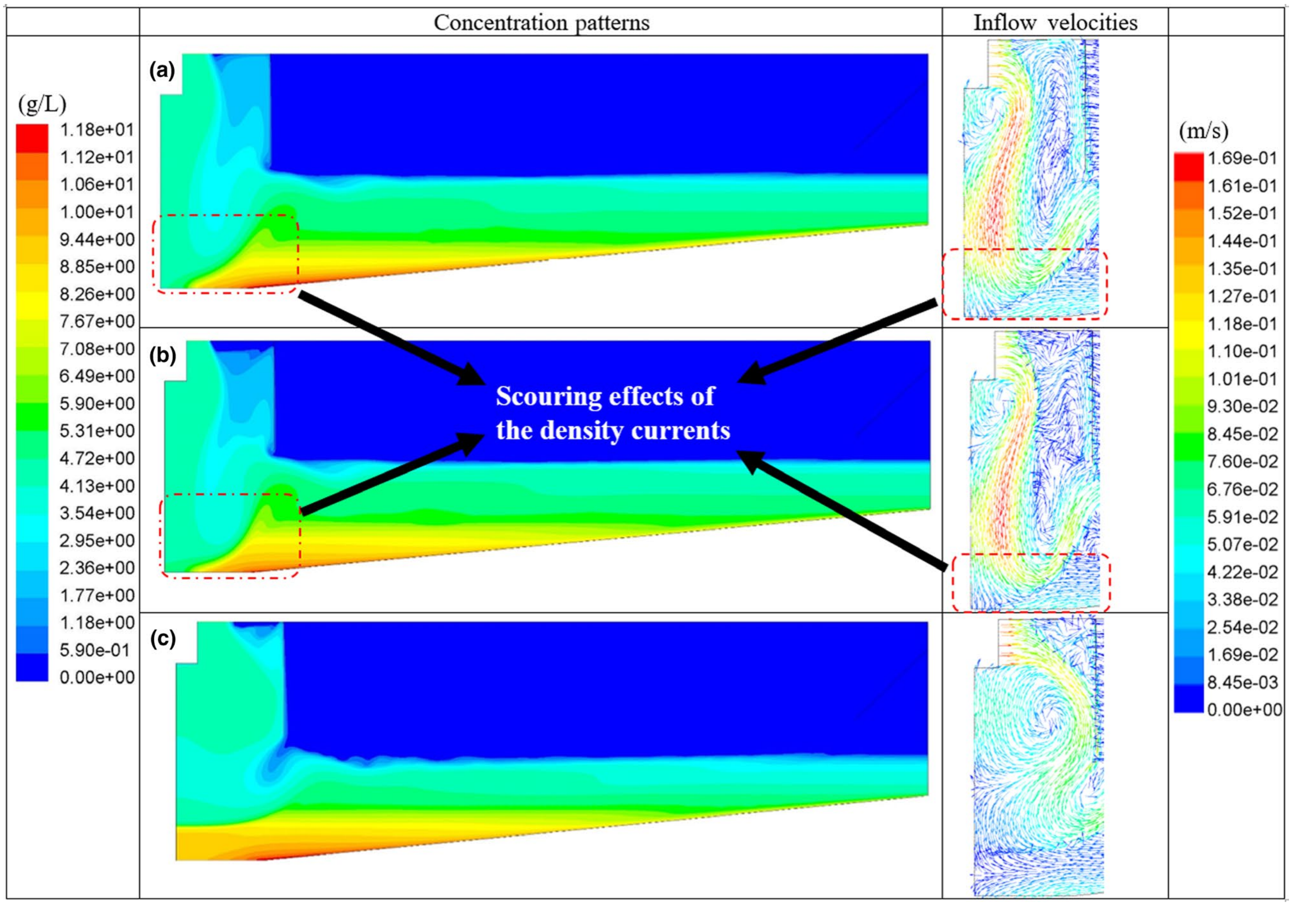

Figure 6. Predictions of the flow and concentration patterns by (a) SKE, (b) RNG *k-ε*, and (c) Realizable *k-ε* turbulence models (adapted from Gao & Stenstrom, 2018a).

tested for a wide range of MLSS concentrations and the CFD results of coupling this new model should be compared with field observations.

$$\frac{dX_l}{dt} = K_B \cdot X \cdot G^2 - K_A \cdot X \cdot X_l \cdot G \tag{9}$$

$$\frac{dX_l}{dt} = K_B \cdot G^2 - K_A \cdot X \cdot X_l \cdot G \tag{10}$$

Table 8. Weighted mean error for ESS, RAS, and SBH (%) for two SSTs

	SKE	RNG	REALIZABLE
Darvill SST			
δ_{ESS} (%)	36.47	35.29	52.94
δ_{RAS} (%)	7.00	5.50	3.00
$\delta_{Darvill}$ (%)	21.74	20.40	27.97
Witney SST			
δ_{ESS} (%)	8.33	3.33	0
δ_{SBH} (%)	8.65	8.65	11.89
δ_{Witney} (%)	8.49	5.99	5.95
$\delta_{Witney + Darvill}$ (%)	15.11	13.19	16.96

where X_l is the concentration of primary particles, X is the MLSS initial concentration, G is the mean velocity gradient, K_A and K_B are the floc aggregation and break up coefficients, respectively.

Conclusions

Over the last 20 years, due to the increase of computational resources and the availability of CFD software, CFD models have been widely applied as a robust and accurate tool for design, optimization, and control of SSTs. This paper has reviewed the early findings and the following conclusions are made.

- The controversy over the relationship between SOR and SST performance can be largely explained by the prediction of the CFD model. The predicted results show that shallow SSTs (<4 m) have poorer performance relative to deep SSTs (>4 m). The shallow SSTs have density currents which scour particles to the effluent zones of the SST, which makes the area available for sedimentation more important. Deep SSTs do not scour particles into the effluent zones and the area available for sedimentation is less important.

- The prediction difference between G_b-decoupled and G_b-coupled turbulence models is significant in an SST with poor baffling structures but negligible in an SST with good baffling structures. Therefore, G_b is a buoyancy correction term to correctly predict the performance of an SST with poor baffling structures.
- Evaluation of parameters used in the CFD models indicates that none of the performance indicators (ESS, SBH, and RAS concentration) is sensitive to the change of the values of buoyancy coefficient (C_3) in the TDR equation. Additionally, only SBH is sensitive to the change of turbulent Schmidt number (σ_c) in the sludge transport equation. Therefore, C_3 can be removed from the TDR equation to improve the rate of convergence and reduce computing time. σ_c can be used to adjust SBH, when ESS and RAS are well calibrated to the field data.
- Temperature is a dominant factor affecting both the performance of PSTs and the type of density currents that are produced. Surface currents are produced when the inlet temperature is higher than the temperature in PSTs, and vice versa.
- Influent temperature variations, surface heat exchange, and MLSS concentrations are all major factors affecting the performance of SSTs. Also, high MLSS concentrations, typically occurring in ASPs, will overcome the effect of inlet temperature, resulting in bottom currents. Therefore, MLSS concentration is the dominant factor in producing density currents in SSTs.
- The existing SVI-based correlations to predict sludge settling velocities produce different flow capacity estimates for a given plant's SVI. Great care must be given when using these SVI correlations to predict the maximum flow capacity.

The following additional research needs were identified in this review.

- The VOF model can be used to study the surface wind effect on the SST performance and the effect of the surface baffling structures to reduce surface wind. Due to the strong surface wind effect on the SST performance, covering the SST surface or adding some vertical baffles on the water surface to reduce the surface wind shear should be considered. Future research can compare the prediction of the SST hydrodynamics with the VOF model results in order to evaluate the benefits of covering or wind baffling.
- Velocity and concentration measurements are needed inside the inlet zone. Since different turbulence models predict significantly different flow capacities and velocity and concentration fields inside the inlet zone, more measurement data are required to select the most accurate turbulence model.
- Further development is needed for settling models that describe the sludge behavior across the entire concentration range as well as considering the turbulent hydrodynamics with measurable parameters.
- An improved sludge rheological model is needed. Instead of fitting a qualitative model by means of parameter calibration, a systematic and repeatable measurement protocol needs to be defined to improve the data reliability.
- The reliability and accuracy of an improved flocculation model such as proposed by Gong et al. (2011) should be tested over a wide range of MLSS concentrations, and the CFD results of coupling this new model should be compared with field observations.

Nomenclature

1D	One-dimensional
2D	Two-dimensional
3D	Three-dimensional
ASP	Activated sludge process
CFD	Computational fluid dynamics
CRTC	Clarifier Research Technical Committee
DSVI	Diluted sludge volume index
EDI	Energy dissipating inlet
EE	Eulerian-Eulerian
EL	Euler-Lagrange
ESS	Effluent suspended solids
LES	Large eddy simulation
MLSS	Mixed liquor suspended solid
NS	Navier-Stokes
PST	Primary settling tank
RANS	Reynold Averaged Navier-Stokes
RAS	Returned activated sludge
SBH	Sludge blanket height
SKE	Standard k-ε model
SLR	Sludge loading rate
SOR	Surface overflow rate
SS	Suspended solids
SST	Secondary settling tank
SSVI	Stirred sludge volume index
SVI	Sludge volume index
SWD	Side wall depth
TDR	Turbulent dissipation rate
TKE	Turbulent kinetic energy
VOF	Volume of Fluid
WEFTEC	Water Environment Federation Technical Exhibition and Conference
WTP	Water treatment plant
WWTP	Wastewater treatment plant

Data Availability Statement

The three programs we used are commercially available and we have referenced them. All the data are from previously published studies, which we have referenced and are available Web of Science and Google Scholar databases.

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