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A force-based mechanistic model for describing activated sludge settling process

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ABSTRACT

Sludge settling as the last step in the biological wastewater treatment process substantially affects the system performance, and thus the design and control optimization of the sludge settling process has been frequently investigated with mathematical modeling tools. So far, these models are developed on the basis of the solid flux theory with numerous parameters and complicated boundary conditions, and their prediction results are often unsatisfactory. In this work, a new force-based mechanical model with five parameters was developed, in which five forces were adopted and Newton's law, rather than the flux theory, was used to describe the sludge settling process. In such a model, the phase interactions were taken into account. New functions of hydrodynamic drag, solids pressure and shear stress were developed. Model validation results demonstrate that both batch and continuous sludge settling processes could be accurately described by this model. The predictions of this model were more accurate than those of flux theory-based models, suggesting its advantages in understanding sludge settling behaviors. In addition, this mechanistic model needed to input 5 parameters and set 1 boundary condition only, and could be directly executed by commercial computational fluid dynamics software. Thus, this force-based model provides a more convenient and useful tool to improve the activated sludge settling design and operation optimization.

1. Introduction

Activated sludge process is the most widely used technology in the wastewater treatment (Li and Stenstrom, 2014). In this process, secondary settling tank (SST), as the final treatment unit, separates the suspended biomass from the treated water to produce a clear effluent through gravity sedimentation (De Clercq et al., 2005a; Jin et al., 2003). Thus, the SST performance is crucial to the effluent quality and system operating efficiency. The sludge settling process is a very complex multiphase fluid motion process (Li and Stenstrom, 2014), and the movement characteristics of activated sludge are not well understood yet. This greatly limits the improvement of activated sludge settling performance.

Mechanical models have been proven to be an effective tool to understand such a complex multiphase fluid motion process (Wu, 2010). Since the solids flux theory was developed by Kynch (1952) various empirical settling models based on such a flux theory have been put forward (Dupont and Dahl, 1995; Hartel and Popel, 1992; Jeppsson and Diehl, 1996). With the empirical settling velocity equations in different settling zones, several one-dimensional (1-D) and two-dimensional (2-D) settling models have been developed (Bürger et al., 2013; De Clercq, 2006; De Clercq et al., 2008; Guyonvarch et al., 2015), with a focus on predicting the flow field and velocity as well as sludge blanket height (Plosz et al., 2007; Ramin et al., 2014a, 2014b; Zhang et al., 2015). Recently, a flux theory-based model was combined with activated sludge model (ASM) to evaluate the impacts of high hydraulic loading rate on wastewater treatment plants (WWTPs) (Bürger et al., 2016). In these models, the flux theory is adopted and sludge concentration is used to empirically describe the sludge settling velocity. Actually, sludge settling process is a slow movement process with the joint actions from gravity, buoyancy, hydrodynamic drag, solids pressure and shear stress. In addition, the interactions among phases, e.g., drag force, play a leading role in sludge continuous settling process in the upper part of SST, and have not been taken into account in these models. Furthermore, the prediction results of the sludge settling process, especially

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compression settling, by these flux theory-based models are not satisfactory (Li and Stenstrom, 2014; Ramin et al., 2014b), and the complex boundary conditions in different settling zones have to be set in these models. Therefore, a more appropriate mechanical model is highly desired to describe the complex sludge settling process.

According to the force action analysis of various settling zones, the forces acting on activated sludge include gravity, buoyancy, drag force, solids pressure and solids shear stress. The gravity and buoyancy can be expressed as a net gravitational force, and the equations in Eulerian-Eulerian two-phase fluid method can be directly used. However, the existing equations for drag force, solids pressure and shear stress are not suitable for describing sludge settling process, and the model predictions by these existing equations are inconsistent with the settling process testing results (Fig. S1). The detailed results are listed in Supplementary Material. Thus, it is necessary to develop new equations for modeling the drag force, solids pressure and shear stress. Furthermore, based on the force equations and the Eulerian-Eulerian approach, the sludge settling process can be modeled using the conservation of mass and momentum of both water and solids.

In this work, we aimed to develop a new force-based mechanistic model, which takes gravity, buoyancy, drag force, solids pressure and shear stress into account to describe the activated sludge settling process. Firstly, appropriate drag force, solids pressure and shear stress functions were developed. The equations of solids pressure and shear stress were deduced from the solids concentration profiles and apparent viscosity, and the parameter of drag force was adjusted to suit the settling process. Then, five forces functions were added into the Newton's law to construct the mechanistic model. The four model parameters (i.e., solids density, yield stress factor, gel point and empirical function of viscosity) were directly measured by conducting batch experiments, and one parameter (i.e., particle size) was measured using a laser particle analyzer. Finally, the model was respectively evaluated by batch and continuous settling tests. The batch tests with activated sludge at three levels were conducted in this work, and the batch settling results of activated sludge at six levels from two WWTPs reported by De Clercq et al. (2008) were used to evaluate this model. Furthermore, this model was also validated by the results of sludge continuous settling process in SST from the previous study by Ramin et al. (2014b).

2. Model development

2.1. Model framework

The framework of Eulerian- Eulerian two-phase approach can be applied to simulate sludge settling process. The continuity equations are expressed as Eq. (1) to describe the liquid and sludge phases:

$$\frac{\partial}{\partial t}\left(\alpha_q\rho_q\right) + \nabla\left(\alpha_q\rho_q v_q\right) = 0 \tag{1}$$

where α, ρ and v represent the volume fraction, density, and velocity of each phase, respectively, and q is different phase (liquid or sludge phase). In addition, the momentum equations of liquid and solid phases are described as Eqs. (2) and (3), respectively.

$$\frac{\partial}{\partial t}(\alpha_l\rho_l\mathbf{v}_l) + \nabla\cdot(\alpha_l\rho_l\mathbf{v}_l\mathbf{v}_l) = -\alpha_l\nabla p + \alpha_l\rho_l\mathbf{g} - K_{ls}(\mathbf{v}_l - \mathbf{v}_s) + \nabla\cdot\tau_l \tag{2}$$

$$\frac{\partial}{\partial t}(\alpha_s\rho_s\mathbf{v}_s) + \nabla\cdot(\alpha_s\rho_s\mathbf{v}_s\mathbf{v}_s) = -\alpha_s\nabla p - \nabla p_s + \alpha_s\rho_s\mathbf{g} - K_{ls}(\mathbf{v}_s - \mathbf{v}_l) + \nabla\cdot\tau_s \tag{3}$$

In Eqs. (2) and (3), $\alpha_s\nabla p$, ∇p_s, $\alpha_s\rho_s g$, $K_{ls}(v_l v_l - v_l)$ and $\nabla\cdot\tau_s$ are items of buoyancy, solids pressure, gravity, drag force, and solids shear stress, respectively, where v_l and v_s are the velocity vectors of liquid and solids, g is the gravity acceleration, p is the liquid static pressure, p_s is the solids pressure, K_{ls} is the liquid-solid exchange coefficient, and τ is the stress tensor.

According to the functions of buoyancy, solids pressure, gravity, drag force, and solids shear stress, the liquid and sludge flocs movement processes in the settling process can be described by Eqs. (1)–(3). The appropriate functions of forces are essential to the mechanical settling model.

2.2. Drag force equations

The drag force function for the momentum exchanges between liquid and sludge is described by the Gidaspow function (Gidaspow, 1994; Gidaspow et al., 1992; Lu and Gidaspow, 2003), which is a combination of the Wen-Yu function (Wen and Yu, 1966) and Ergun function (Ergun, 1952). Wen-Yu equation (Wen and Yu, 1966) (Eqs. (4) and (5)) can describe the drag force in dense phase, while Ergun equation (Eq. (6)) (Ergun, 1952) describes the drag force in dilute phase. The particle diameter was determined using a laser particle analyzer (Mastersizer 3000, Malvern Instruments Co., UK). The volume fraction (α_l, 0.8) of solids phase is used to distinguish dilute phase from dense phase. However, the maximum volume fraction of sludge is below 0.8. Thus, the Gidaspow function could not be directly applied to describe the sludge settling process. In this work, the value of α_l was adjusted to appropriately describe the sludge settling process according to the gel point of sludge. The α_l values of the sludge samples from Xiaojiahe, Destelbergen, Deinze and Lundtofte plants were adjusted to 0.0057, 0.0062, 0.0074 and 0.0084, respectively.

$$K_{ls} = \frac{3}{4}C_D\frac{\alpha_s\rho_l|\mathbf{v}_s - \mathbf{v}_l|}{d_s}\alpha_l^{-2.65}(\alpha_l > 0.8) \tag{4}$$

$$C_D = \frac{24}{\alpha_l \mathrm{Re}_s}\left[1 + 0.15(\alpha_l \mathrm{Re}_s)^{0.687}\right] \tag{5}$$

$$K_{ls} = 150\frac{\alpha_s(1-\alpha_l)\mu_l}{\alpha_l^2 d_s^2} + 1.75\frac{\rho_l\alpha_s|\mathbf{v}_s - \mathbf{v}_l|}{\alpha_l d_s}(\alpha_l \le 0.8) \tag{6}$$

2.3. Solids shear stress equation

The solids shear stress contains collisional, kinetic volumetric and frictional viscosities arising from the particle momentum exchange due to the translation, friction and collision. All the present solids shear stress functions contain the term of granular temperature, while the particles' random motion of sludge flocs can be neglected. Therefore, the present equations of solids shear stress are not suitable for describing the sludge settling process (The detailed reasons are given in Supplementary Material). In this work, the solids shear stress of sludge was simplified as apparent viscosity, which was evaluated by using a rotational rheometer (DV-II+PRO, BROOKFIELD, USA). As a result, the relationship between shear stress and sludge concentration could be established.