Multiphysics Simulations of Granular Sludge Characteristics on the Optimization of Effluent Treatment Plant

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Abstract: Waste water treatment processes are considered to be the largest industry in terms of treated mass of raw materials. However, in terms of meeting the stringent environmental pollution norms, there are still many grey areas that need to be addressed. For example, the understanding of the settling behavior of activated granular sludge in the secondary settler of an Effluent Treatment Plant (ETP). Knowledge of this aspect is essential for the plant designers to determine the efficiency of wastewater treatment in particular. This apart, it reduces the costs related to waste sludge dewatering and disposal and improves the separation of biomass and treated effluent quality requirements before the latter is discharged to the surface water. Any failure in the settling tank, either due to sludge bulking or excessive loss of sludge deteriorates the effluent quality that could lead to uncontrolled low sludge ages and a reduction of efficiency in the aeration tanks.

In order to capture the basic physics of a sludge settling, the authors did simulate a model of an activated sludge granule falling in water using COMSOL Multiphysics software tool with free flow simulation in a moving co-ordinate system coupled to an ODE which describes the sludge motion. The effect of particle size, and its density on the settling time was investigated in an effort to showcase the benefits of multiphysics modeling for efficient and eco-friendly waste water treatment.

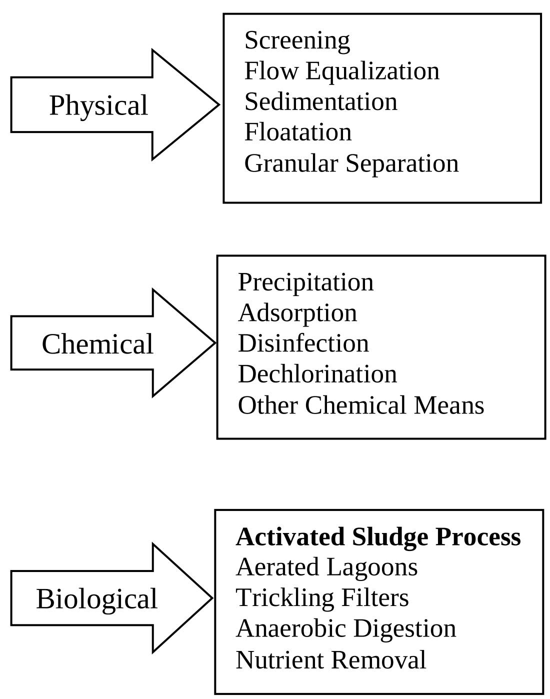
Keywords: Granular sludge, ETP, COMSOL, BOD, COD, ODE, Multiphysics, Water treatment, Multiphase flow, fluid flow.

1. Introduction

The effluent treatment is becoming more and more challenging in Today's highly populated, industrialized world with the diminishing water resources, increasing waste-water disposal costs, and stricter discharge regulations [1-10]. The design optimization of ETP, therefore, becomes very much critical and essential to carry out the various physico-chemical and biological processes that are involved to achieve the required quality norms such as Biological Oxygen Demand (BOD) and Chemical Oxygen Demand (COD). The activated sludge process (ASP) is the most generally applied biological wastewater purification technique adopted in any advanced ETP operations. The present paper deals with the simulation / modeling aspects of the granular sludge formation and flow dynamics in ASP using the state of the art COMSOL software.

1.1 Overview of Waste Water Treatment

In general, the waste water treatment methods are broadly classifiable into physical, chemical and biological processes as illustrated in the following scheme:



Waste Water Treatment Scheme

1.2. Activated Sludge Process

This paper focuses mainly on the activated sludge process involved in the biological treatment of effluent water in an effort to aid the plant designers to reduce the concentration of, organic and inorganic compounds thereby reducing BOD and COD values to the required levels of environmental standards. There are two main types of biological processes; these involve suspended microbial growth, e.g. 'activated sludge' and attached microbial growth, e.g. 'bio-film'. ASP has been the technology of choice for the treatment of waste water to a high level of final effluent quality. This technology though yields excellent COD, nitrogen and phosphate removal always had one flaw due to poor floc or granules settling. With the development of aerobic granular activated sludge the problem has been solved, with the microbiological mass being in the form of granules, a close approximation to spherical particles.

This paper thus considers the settling behavior of a spherical granular sludge for the modeling and simulation studies using the physical parameters such as density and particle size to understand the physics of settling. The aerobic sludge granular process allows the operator to have a single tank treatment and opens up a simple approach to process configuration design and development leading to ETP optimization. This could result in considerable savings in terms of plant area requirements, capital expenditure, and other operational and maintenance costs.

2. Optimized Sludge Granular Settling

In order to achieve simplicity, and overcome the complexities of flocculent and hindered settling, we have considered the settling of a discrete particle in a dilute aqueous suspension. Discrete settling of small spherical particle in water is defined by Stokes law. The drag effects of the sludge particle are included in the modified Stokes law .

The basic equations are valid only for low Reynolds number regime. It shows that the most efficient way of increasing the settling velocity of a sphere would be to increase its radius due to the square factor. In reality, however, the problem is that flocs are not spheres. Larger the floc, better it settles; but it will never settle as well as a sphere. The spherical granular sludge hence, presents the optimum cross sectional area to volume ratio, allowing for optimized settling. Advanced research works are in progress at the plant level on reducing the settling time required for activated sludge by forming dense flocks or by using biofilm reactors. The mechanism of microbial aerobic granulation and settling behavior is still a topic of considerable discussion, owing to the complexity of aerobic granulation in the biological treatment of waste water. A numerical model is best suited for investigating the settling behavior of sludge in practical applications.

3. Numerical Simulations

Gravity settling is an economical method of segregation of sludge particles. If the waste water tank fluid is moving at a controlled velocity, the sludge particles can be sorted in separate containers according to the time it takes for them to reach the bottom. A COMSOL model has been developed to simulate the sludge particle settling in water. The sludge particle accelerates from a standstill position and rapidly reaches its terminal velocity.

The single-phase fluid-flow is governed by Navier-Stokes equation. The continuity equation represents the conservation of mass; vector equation representing the conservation of momentum, conservation of energy equation and the constitutive relation for Newtonian fluid are given below, respectively [11].

$$\frac{\partial \rho}{\partial t} + \nabla.(\rho u) = 0$$

$$\rho \frac{\partial u}{\partial t} + \rho(u.\nabla)u = \nabla.(-pI + \tau) + F$$

$$\rho C_p \left\{\frac{\partial T}{\partial t} + (u.\nabla)T\right\} =$$

$$-(\nabla.q) + \tau : S - \frac{T}{\rho}\frac{\partial \rho}{\partial T}|_p \left\{\frac{\partial \rho}{\partial T} + (u.\nabla)p\right\} + Q$$

$$\tau = 2\mu S - \frac{2}{3}\mu(\nabla.u)I$$

Where,

ρ is the density, kg/m3
u is the velocity vector, m/s
p is pressure, Pa
τ is the viscous stress tensor, Pa
F is the volume force vector, N/m3
Cp is the specific heat capacity, J/ (kg•K)
T is the absolute temperature, K
q is the heat flux vector, W/m2
Q is the heat source, W/m3
S is the strain-rate tensor
μ is the dynamic viscosity, Pa·s

Fluid flow simulation in a moving coordinate system was implemented in COMSOL by coupling the fluid flow to the sludge particle motion with an ordinary differential equation (ODE). A parametric model was developed to study effect of sludge particle size, sludge density and the fluid medium. Appropriate material properties, boundary condition and mesh parameters were assigned to the model. A numerical design of experiments was conducted to study the effect of sludge density, sludge particle size and fluid density on the settling velocity of the sludge particle using parametric modeling feature. A comparison with analytical model was also performed for benchmarking the simulation model. The simulation results are detailed the next section.

4. Results and Discussion

The simulation results are summarized in this section. The effect of sludge density, sludge particle size, density of aqueous medium are investigated as function of velocity of the sludge particles.. The physical parameters of the particle such as its density and spherical radius are assumed with a wider range to highlight the performance under modeling conditions. Similarly, the density variations with respect to effluent water undergoing biological treatment are taken at extreme levels to broadly study the settling behavior of sludge granules. Figure 1 shows the contour plots for a typical sludge size, sludge density and fluid density. Figure 2 shows the velocity contour plots around the sludge particle for a density of 2000 kg.m2 and a size of 0.005 m. Figure 3 shows the velocity contour plots around the sludge particle for a density of 2500 kg/m2 and a size of 0.002 m. The contour plots help us to identify the flow pattern for optimal design of settling tank.

The graphical illustration of simulation results are shown in Figures 4-6. Figure 4 shows the effects of water density on for a given sludge particle. The reduction in water density increases the settling time. Further, it can be observed that the reduction in density difference between sludge and water reduces the settling time.

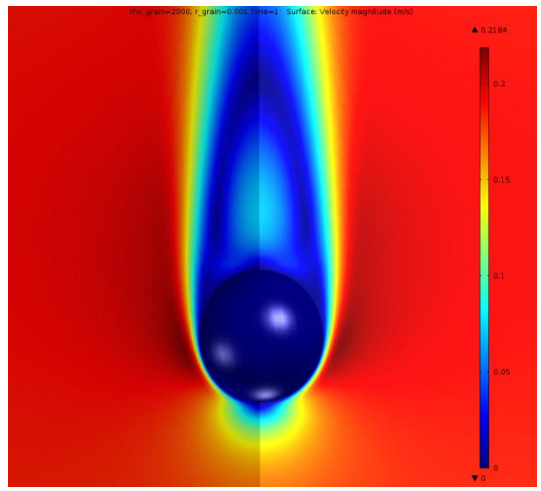


Figure 1 Typical velocity contour plots around the sludge particle in the fluid medium.

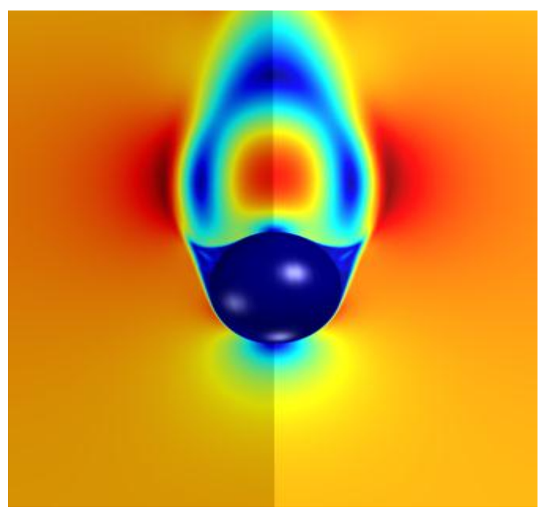


Figure 2 Typical velocity contour plots around the sludge particle for a density of 2000 kg.m2 and a size of 0.005 m.

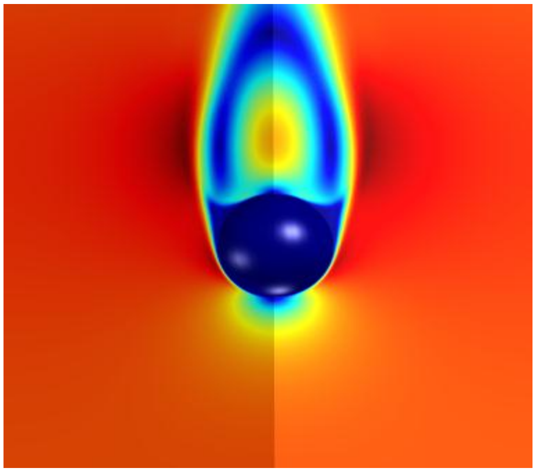


Figure 3 Typical velocity contour plots around the sludge particle for a density of 2500 kg/m2 and a size of 0.002 m.

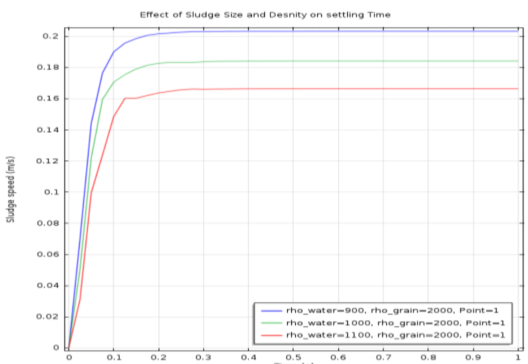


Figure 4 Illustration on the effect of water density on the settling speed of sludge.

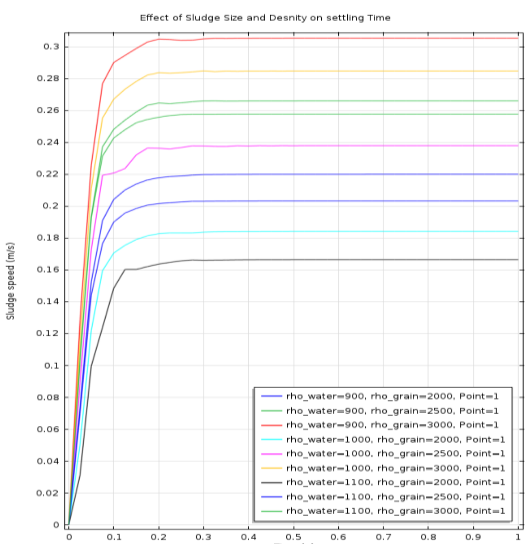


Figure 5 Illustration on the effect of water and sludge density on settling speed.

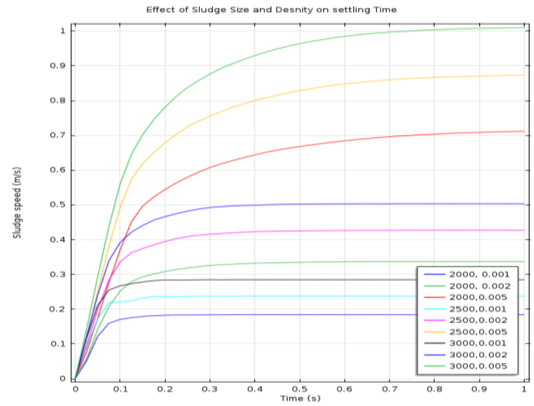


Figure 6 Illustration on the effect of sludge density and sludge particle size on settling speed.

Figure 5 shows the effect of water density and grain density on the settling time of the sludge. The water density was changed from 900 to 1100 kg/m2 and sludge density from 2000 to 3000 kg/m2. The increase in density difference between sludge and water increases the settling time. This behavior is in accordance with the Stokes law.

Figure 6 shows the effect of sludge density and sludge particle size on the sludge terminal speed. For a given density, increase in particle size increases the settling time. Increase of both density and size of the sludge particle increases the settling time.

The results show that for a given set of properties of the sludge, the settling behavior can be estimated and used for the design of the biological method of the effluent treatment plant. The simulation data also compare well with the experimental observation and previously published results. The numerical modeling with parametric optimization can be ultimately used for the efficient optimization of ETP.

5. Conclusions

A brief overview of the waste water treatment was given along with a detailed account of the activated sludge process, the essential part of the biological treatment. The main objective was to demonstrate numerical modeling capability for ETP design and optimization. Hence, the sludge settling process was chosen for the demonstration. The analytical equations and basic physics related to sludge settling process were illustrated for better understanding the complexities of ASP. The numerical model and its implementation of fluid flow coupled with moving boundary conditions were detailed. The effects of sludge particle density, sludge particle size and water density on the sludge settling speed were investigated. Numerical modeling is a powerful tool to design waste water treatment plants. Our present efforts indicate that one can use COMSOL Multiphysics modeling for the optimization of ETP for the physico-chemical and biological treatments of waste water. As demonstrated for the sludge settling behavior, the multiphysics optimization can be used to save the plant operational costs and to meet the stringent quality standards of the treated effluent.

6. References

1. A. Nor Anuar et al., Water Science & Technology, **56**, 55- 63, QIWA (2007)
2. Y. A_nimelech et al., Aquacultural Engineering, **25,** 25–33 (2001)
3. P. Vega et al., Proceedings of European Congress of Chemical Engineering, ECCE-6, Copenhagen (2007)
4. American Public Health Association; American Water Works Association; Water Pollution Control Federation Standard Methods for the Examination of Water and Waste water. Washington, D.C. (1998).
5. A.D.Andreadakis, 'Physical and chemical properties of activated sludge floc.' Water Res. **27**(12): 1707-1714 (1963)
6. Bisogni et al., 'Relationship between biological solids retention time and settling characteristics of activated sludge', Water Res. **5,** 753 (1971)
7. Dammel et al., 'Density of activated sludge solids', Water Res. **25**(7), 841-846 1991)
8. Ford et al., 'Effects of process variables on sludge floc formation and settling characteristics'. J. Water Pollut. Control Fedn., **39,** 1850 (1967)
9. Economic and Social Commission for Western Asia, 'Waste-Water Treatment Technologies: A General Review', United Nations, New York (2003)
10. Hoon Jang et al., 'The case for variable density: A new perspective on activated sludge settling', WEFTEC (2006)
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7. Acknowledgements

The authors would like to thank the Research and Innovation division of ATOA Scientific Technologies for the 100:20 research funds and the approval for publication of this paper.