Computational fluid dynamics modelling of a transient solids concentration in a lagoon

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Abstract Investigation of slurry flows is important for the mineral industry, biomass processing and waste processing. In the design of slurry handling systems such as channel flows, separators where solids concentrates are separated from clear liquid streams, knowledge of physics underlying slurry flows is required. In this study, slurry flows in tanks have been investigated. The transient profiles of the solids concentration along the length have been modelled using computational fluid dynamics(CFD). This investigation examines multiphase flows with settling solids in a non-Newtonian flow. The dynamical model gives guidance in determining formation accumulation of solids as a sludge blanket. In addition the clear liquid solids interface position has been determined this is needed for the recycle of the clear water for water conservation.

1 Introduction

Biological treatment processes are widely used in wastewater treatment plants. One of the key factors that control the efficiencies of the plant is the separation processes that remove the solids concentrated streams from the clear liquids as discussed by Li([2]). The resulting sludge is caused by sedimentation that consists of settling solids which have to be of sufficient size to get an efficient settling velocity. In order to accomplish this the fluid dynamics underlying the multiphase non-Newtonian flow needs to be understood. For wastewater systems this is done in large tanks or circular basins in order to achieve enough hydraulic time to settle the solids flocs into a sludge layer. In a previous work, Zhou and McCorquodale([1]) modelled the flow in a rectangular tank in a simplified model which did not consider the rheological effects of the solids. Lakehal et al([5]) further included non-Newtonian effects in

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modelling sludge flows in a wastewater basin. In this investigation, we adopted the approach used by Lakehal et al([5]). We combine the rheology of wastewater with large scale settling in turbulent flows and investigated the sludge flow in a lagoon. Our model flows is represented by a two dimensional tank that is 8 meters high and 50 meters in length. In this tank we assume a feed of slurry at one end in the top three meters. There are two outlets in the next end; a top outlet flow for the clear liquid withdrawal, and the bottom outlet for the sludge withdrawal; both these outlets are one meter in length. To our knowledge this approach has not been used on such scale for wastewater systems.

2 Governing equations

The system of equations include the continuity equation and the general equations of motion. They have been modified to include the complex physics of the clarification process. The overall multiphase flow process is turbulent and we have used the $k-\varepsilon$ model for this. Detailed explanation of the symbols need to be referred to Lakehal et al([5]). We have incorporated these modifications as User Defined Functions(UDFs) into Fluent([6]).

Continuity and X - Momentum Equations

$$\frac{\partial V_x}{\partial x}+\frac{\partial V_y}{\partial y}=0 \tag{1}$$

$$\begin{aligned}\rho\frac{\partial V_x}{\partial t}+\rho\frac{\partial V_x^2}{\partial x}+\rho\frac{\partial V_xV_y}{\partial y} &= -\frac{\partial p}{\partial x}+\frac{\partial}{\partial x}(2\mu_t\frac{\partial V_x}{\partial x})+\\ &\frac{\partial}{\partial y}[\mu_t(\frac{\partial V_x}{\partial y}+\frac{\partial V_y}{\partial x})]+\frac{gC(\rho_p-\rho_w)}{\rho_w}\end{aligned} \tag{2}$$

The last term in this equation is a source term for momentum in the X direction. The density difference provides a buoyancy effect.

Y - Momentum Equations

$$\begin{aligned}\rho\frac{\partial V_y}{\partial t}+\rho\frac{\partial V_y^2}{\partial y}+\rho\frac{\partial V_xV_y}{\partial x} &= -\frac{\partial p}{\partial y}+\frac{\partial}{\partial x}(\mu_t(\frac{\partial V_x}{\partial y}+\frac{\partial V_y}{\partial x})+\\ &\frac{\partial}{\partial y}[2\mu_t(\frac{\partial V_x}{\partial y})]\end{aligned} \tag{3}$$

The turbulence is described by k and ε by

$$\begin{aligned}\rho\frac{\partial k}{\partial t}+\rho\frac{\partial V_xk}{\partial x}+\rho\frac{\partial V_yk}{\partial y} &= \frac{\partial}{\partial x}[(\mu+\frac{\mu_t}{\sigma_k})\frac{\partial k}{\partial x}]+\\ &\frac{\partial}{\partial y}[(\mu+\frac{\mu_t}{\sigma_k})(\frac{\partial k}{\partial y})]+G_k+G_b-\rho\varepsilon\end{aligned} \tag{4}$$

$$\rho\frac{\partial\varepsilon}{\partial t}+\rho\frac{\partial V_x\varepsilon}{\partial x}+\rho\frac{\partial V_y\varepsilon}{\partial y}=\frac{\partial}{\partial x}[(\mu+\frac{\mu_t}{\sigma_\varepsilon})\frac{\partial\varepsilon}{\partial x}]+\frac{\partial}{\partial y}[(\mu+\frac{\mu_t}{\sigma_\varepsilon})(\frac{\partial\varepsilon}{\partial y})]+ C_1\varepsilon\frac{\varepsilon}{k}(G_k-C_3\varepsilon G_b)-\rho C_2\varepsilon\frac{\varepsilon^2}{k} \quad (5)$$

The convection-diffusion equation is used to compute the field of suspended solids concentration C

$$\rho\frac{\partial C}{\partial t}+\rho\frac{\partial(V_x+V_s)C}{\partial x}+\rho\frac{\partial(V_yC)}{\partial y}=\frac{\partial}{\partial x}\left[\frac{\mu_t}{\sigma_c}\frac{\partial C}{\partial x}\right]+\frac{\partial}{\partial y}\left[\frac{\mu_t}{\sigma_c}\frac{\partial C}{\partial y}\right] \quad (6)$$

The value for the turbulent Schmidt number is 0.7 which is a typical value for free flow and near wall flow as applied to this situation. The solids settling velocity V_s is modelled using a settling function of Takacs[3]).

$$V_s=V_{s0}exp[-r_h(C-C_{ns})]-V_{s0}exp[-r_p(C-C_{ns})] \quad (7)$$

This approach adequately describes the hindered settling of activated sludge.
To physically characterize the rheology of the sludge, we have used the Bingham turbulent constitutive equation used by Dahl[4]) to characterize the slurry. The yield stress τ_b is function of the solids concentration. The shear stress is given as

$$\tau_{xy}=-(\frac{\tau_b}{2\gamma}+\mu_p+\mu_t)(\frac{\partial V_x}{\partial y}+\frac{\partial V_y}{\partial x}), \quad (8)$$

where the turbulent viscosity μ_t is dependent on k and ε,

$$\mu_t=\rho C_\mu\frac{k^2}{\varepsilon},$$

and the yield stress τ_b is given by

$$\tau_b=\beta_1 exp(\beta_2 C).$$

Table 1 lists the values given to the parameters that are used in this simulation

3 Results and Discussion

We are interested in flows in lagoons with long lengths; in which in this case is 50 meters long and 8 meters high. The initial condition has water in the tank with no solids and zero velocity. The solids are introduced in the inlet stream at a steady

Table 1 Parameters used for the simulation

Parameters	Description	Value
U_in	Inflow Velocity	0.019 $\frac{m}{s}$
C_in	Inflow Particle Concentration	3.2 $\frac{kg}{m^3}$
ρ_p	Dry Particle Density	1450 $\frac{kg}{m^3}$
ρ_w	Clear Water Density	1000 $\frac{kg}{m^3}$
σ_c	Schmidt Number	0.7
US0	Reference Settling Velocity	0.005 $\frac{m}{s}$
RH	Floc Settling Parameter	0.7 $\frac{m^3}{kg}$
RP	Colloidal Settling Parameter	5 $\frac{m^3}{kg}$
CMIN	Nonsettleable Concentration	0.01 $\frac{kg}{m^3}$
USMAX	Maximum Settling Velocity	0.002 $\frac{m}{s}$

flow of 0.019 m/s, in which the concentration of solids is 3.2 kg/m3 as shown in Table 1. This work investigates the accumulations of solids as a sludge blankets by a transient two dimensional analysis.

The systems Equations (2) - (8) were solved using finite volume method in ANSYS Fluent 14.2. The source momentum terms and the rheological properties are implemented by User Defined Functions (UDFs) of Fluent ([6]). Using a similar approach to Lakehal et al ([5]) we have solved slurry model to depict the dynamics of solids concentration in a lagoon. The suspended solids concentration is determined by C in Equation (6). The buoyancy effects that result from the solids settling due to gravity with the density differences cause temporary circulation effects with the resultant non-uniform sludge layering effects.

The 2D model transient solution provides the profiles of solid concentration, designated by Scalar 0 at different times. Figure 1 and Figure 2 we present the contours on the solids concentration(Scalar 0) at times t = 1000s and t = 6000s respectively. In the case of 1000s, as shown in Figure 1, high concentration flow of solids from the inlet are pulled by gravity along the wall until the bottom is reached. After the solids reach the bottom they move along the length towards the outlets due to the momentum of the flow. However because of gravity there is a stratification with higher concentration of solids at about $1.5kg/m^3$ along the bottom. At about 12 meters from the end there is a solids accumulation spot in the bottom of about $5kg/m^3$. The reason for this is the recirculation in flow. This causes stagnation in which the gravity effects dominate and cause a pile up of solids this point. Note that as the flow get approaches the end, at about 5 meters there is another smaller solids build up on the bottom. This is again caused by the circulatory currents. In this case since the overall solids concentration is higher because if dispersion mixing, the overall settling effect is lower since the negative buoyancy effect is decreased. However, at the top exit point we see a slight increase in solids concentration to about $0.5kg/m^3$, which results in turbid liquid to be extracted from the top end.

Figure2 contours shows a solids concentration at t = 6000s which approaches a quasi-steady-state in which a distinctive separation layer between the solids and

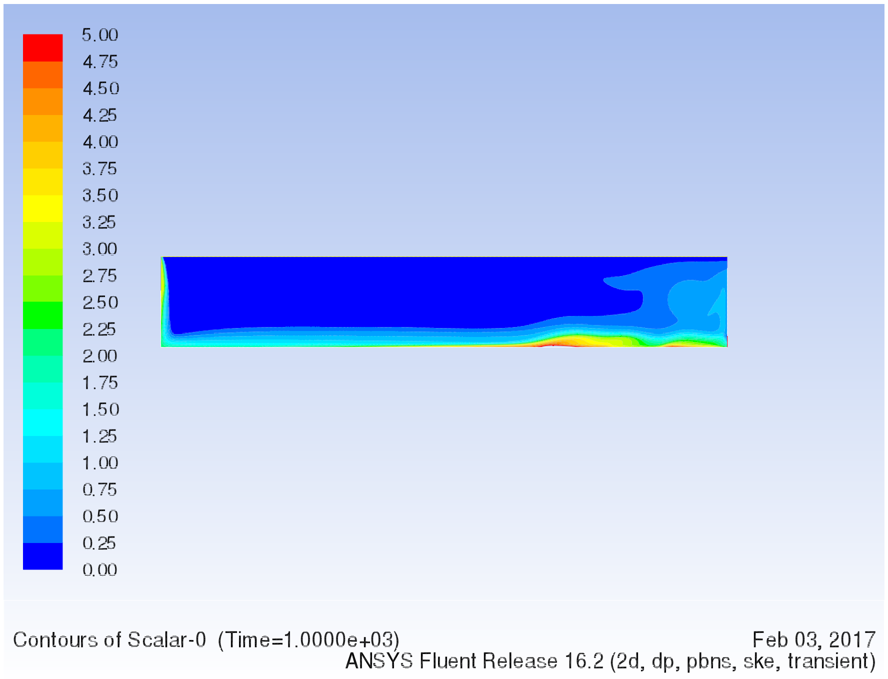

Fig. 1 Variation of solids concentration at T=1000s.

water has formed. This top layer is free of solids and can be recycle for use as water. Also, it can be seen from Figure2 that the solids concentration increases sharply from approximately $0.5kg/m^3$ to about $2kg/m^3$. Furthermore we also note that a thin layer of high concentration of solids is greater than $4.5kg/m^3$ along the bottom. The thickness of this layer is approximately constant after about 4 meters from the inlet wall.

We have quantified the solids concentration profiles at these times by extracting numerical results of the biomass(solids) concentration along three positions in the flow direction (y = 4, 20 and 40 meters). These are shown in Figure 3 (t = 1000s), Figure 4(t = 6000s). In Figure 3, we see that overall solids concentration increases along the y axis. This is consistent with the fact that near the end the recirculation causes stirring of the solids and hence increases the concentration. Also it should be noted that the inlet is constantly feeding solids which initially flow along the bottom along the y axis and then circulate near the end causing an increase in concentration with height. We confirm that a steady-state is approached at 6000s as shown in Figure 4 which shows that the Scalar 0 value jumps from approximately $0kg/m^3$ to greater than $9kg/m^3$ at a depth of 3 meters from the surface. From Figure 4 we can also confirm a formation of a highly concentrated layer of about $3kg/m^3$ to $9kg/m^3$ near the bottom.

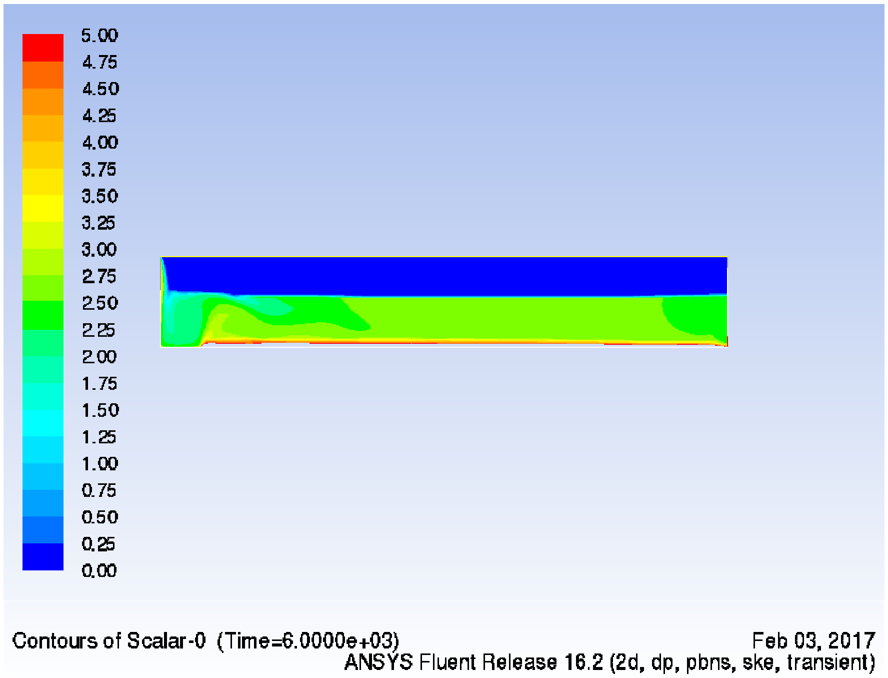

Fig. 2 Variation of solids concentration at T=6000s

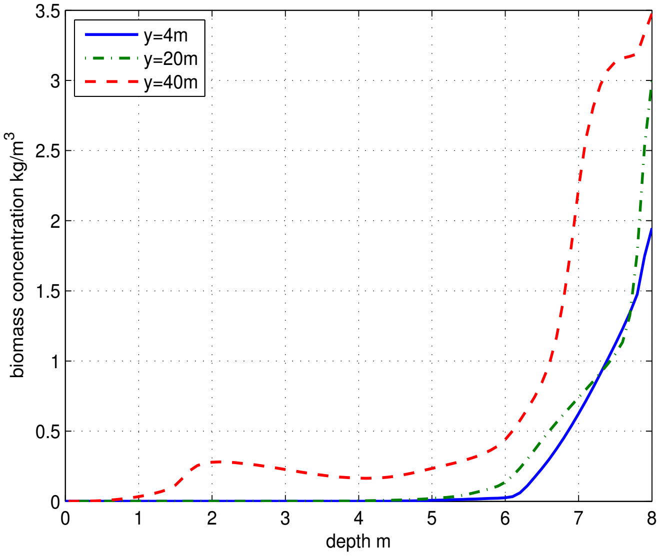

Fig. 3 Variation of solids concentration profiles at T=1000s

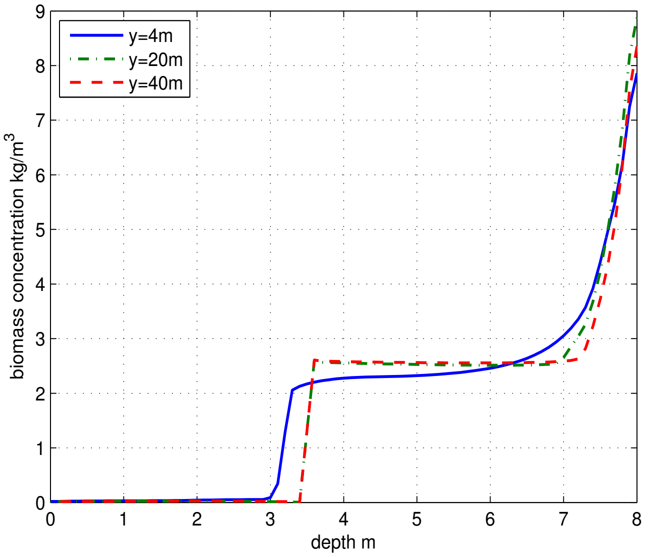

Fig. 4 Variation of solids concentration profiles at T=6000s

4 Conclusion

The results for solids concentration at t = 1000s show two pockets of solids build up on the bottom near the outlet. This is due to flow recirculation due to a combined effect of turbulence in the slurry and the effect of gravity. However it is noticed that for a longer time of 6000 s these pockets of solids disappear and a quasi-steady state is reached with a thin layer of concentrated solids at the bottom and a distinctive separation of clear water and solids starts at about 3 meters from the surface. Thus it can be concluded that providing we supply an adequate outlet near the bottom of the lagoon the solids buildup should be stabilized. Also, overall we have shown that this method can be used to determine the transient concentration profile which is an important issue for lagoon solids management for providing guidelines for water treatment strategy and sludge removal maintenance schedule. Future work will be focussed on parameter modelling for optimal design of lagoons.

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