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International Journal of Environmental Sciences and Research
Vol. 2, No. 1, 2012, pp. 129-133

The implementation of hydrodynamic model in water treatment to estimate turbidity removal

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Abstract

Direct evaluation of the performance and efficiency of sedimentation tanks could more costly and time consuming. Mathematical model can be a good alternative to observe the hydrodynamic in a sedimentation basin. Mathematical model was constructed from two hydrodynamic equations, namely the continuity equation and momentum equation. This research aims to study mathematical models of settling flocs patterns in rectangular sedimentation tanks based on the hydrodynamic model (HPAs Model) mathematical formulation. Research includes the formulation of mathematical models whose results will be visualized with Mathlab, the acquisition of primary data using physical models, testing the model using Mathlab with the primary data input. The result of running the program input data showed variations in settling flocs patterns in the sedimentation basin which explained that the settling zone starting from the inlet to the outlet there is a decrease of flow velocity pattern (u), Reynolds numbers (NRe), Froude numbers (NFr) and turbidity concentration (c). In addition, a decrease also occurred along with the depth of the settling basin zone. As for the pattern of flocs settling velocity (w) there was increasing from the inlet to the outlet and along with the depth of the basin. Formulation of mathematical model of settling flocs patterns can be used through parameter flow velocity pattern, the pattern of settling velocity and concentration patterns of turbidity, NRe and NFr. Simulation showed that turbidity can be removed higher than 80%. Implementation of the HPAs model still in laboratory scale and the research will continue to validate the model by using pilot scale implementation, such as in water works.

Keywords: Hydrodynamic model, sedimentation tank, settling flocs

1. Introduction

Generally, sedimentation tanks are characterized by hydrodynamic phenomena, such as density water, Eddy's currents, sensitive to temperature changing and wind effects. As it was well known, there were two main types of sedimentation tanks: primary settlers (such as individualized settlers used for grit removal) and secondary settlers (those in the activated-sludge process or chemical coagulation processes were also sedimentation tanks, where flocs were removed by hindered gravity), the latter ones have an important purge flow rate (Ahmadi, et.al., 2007). Many factors could be influenced the performance and efficiency of sedimentation tank such as velocity settling of flocs and geometry basin (Razmi, et.al., 2009),concentration and suspended particles characteristic (Sammarrae, 2009), effect of turbulence flow (Gou et.al, 2009), inlet and outlet design (Ahmadi, et.al., 2007), baffle used to flow control (Athanasia, et.al., 2008b), detention time (Athanasia, et al.,2008a).

Direct evaluation to performance and efficiency of sedimentation tank require more costly and time consuming. Mathematical modeling was one of the alternative ways to determine of the flow field and hydrodynamics conditions in settling tanks. Many researchers have used mathematical modeling with same principles but in different methods (Lopez et.al., 2007; Kantoush, et.al., 2008). One of the mathematical model is Hydrodynamic Pollutant Dispersion in River (HP2S). The model is based on conservation law of mass and energy, mathematics structure of differential partial through Leap Frog explicit finite difference numerical method that model visualized by using Mathlab computer program (Karnaningroem, 2005).

This current research used HPAs model to make formulation of mathematical model of flocs precipitation patterns in rectangular sedimentation tanks and to analyze the effect of hydrodynamic to the settling flocs. It based on transport mechanism in flocs dispersion before it settled was analogized to pollutant transport phenomenon in river.

2. Materials and Methods

2.1 Optimizing coagulant dose: Jar test was the experimental to determine the optimum coagulant dose, which it used alum, poly aluminium chloride (PAC) and mixture of alum and PAC. The experimental settling flocs consist of a coagulation tank and flocculation tank both with turbine mixer, a rectangular sedimentation tank.

2.2. Providing instrument: Scaled physical models were based on a similarity theory, which used a series of dimensionless parameters that fully or at the least, partially characterize the physics. The choice of a scaling factor $n=Lp/Lm$, or length scale ratio, to be used in the experiments, was determined by the objectives of the research. According to the length of the tested section and laboratory constraints, the present laboratory model has been designed with horizontal and vertical scales of $n_h=n_v=25$. The selected flow rates were selected to take into account the tank dimensions according to Reynolds (NRe) and Froude numbers (NFr). Runs were carried out with injection optimum coagulant dose for alum was 86 ppm, PAC 35 ppm and mixture alum and PAC 70 ppm. If failure flocs formed then must be selected flow rate again. Finally, running carried out with flow rates 5 ml/s, 10 ml/s and 15 ml/s.

2.3. Identification pattern: For identification of flow patterns, fluorescent was injected and the evolution of the color vein was observed. It is first step to the study hydrodynamic condition in sedimentation tanks, so that the observed phenomena (recirculation, preferential flow paths, etc.) could be used as a qualitative orientation in the comparison of quantitative models. For identify of settling flocs pattern, Smart Spectrophotometer took samples at 10 different points of surface basin into account turbidity.

2.4. Mathematical formulation: Formulation for mathematical modeling based on formulation of mathematical in hydrodynamic model (Karnaningroem, 2005), which mathematical models are based on the law of conservation of mass, conservation laws and momentum transport phenomena. Results formulation visualized with Mathlab program that obtained model flocs precipitation patterns.

2.5. Computer simulation: The HPAs model was prepared with visualization by Mathlab program after changed axis y as width of river became axis z as depth of tank. Experimental data were used for simulation HPAs model. Next simulation conducted with length sedimentation tank variation to observed hydrodynamics condition. Outputs of running model were visualization of horizontal velocity flow, settling flocs pattern, turbidity, and NRe and NFr.

3. Theory and calculations

Mass conservation equation (Eq.1) simplifies to Equation 4 because the mass flow changes resulting from changes to the length and depth of the basin and the runoff or the source of the mass inside, where the sedimentation basin is the injection of coagulant.

$$\left(\frac{\partial \rho}{\partial t}+\frac{\partial \rho u}{\partial x}+\frac{\partial \rho w}{\partial z}\right)=q \qquad \text{........(4)}$$

With the application Leap Frog method, then it becomes Eq.5

$$\rho_{i,k}^{n+1}=q_{i,k}^{n}+\rho_{i,k}^{n-1}-\frac{\Delta t}{\Delta x}\rho_{i,k}^{n}(u_{i+1,k}^{n}-u_{i-1,k}^{n})-\frac{\Delta t}{\Delta x}u_{i,k}^{n}(\rho_{i+1,k}^{n}-\rho_{i-1,k}^{n})-$$
$$\frac{\Delta t}{\Delta z}\rho_{i,k}^{n}(w_{i,k+1}^{n}-w_{i,k-1}^{n})-\frac{\Delta t}{\Delta z}w_{i,k}^{n}(\rho_{i,k+1}^{n}-\rho_{i,k-1}^{n}) \qquad \text{....(5)}$$

Based on non-linear stability analysis, then it becomes Eq.6.

$$\rho_{i,k}^{n+1}=q_{0}+\rho_{i,k}^{n-1}-\frac{\Delta t}{\Delta x}\rho_{0}(u_{i+1,k}^{n}-u_{i-1,k}^{n})-\frac{\Delta t}{\Delta x}u_{0}(\rho_{i+1,k}^{n}-\rho_{i-1,k}^{n})-$$
$$\frac{\Delta t}{\Delta z}\rho_{0}(w_{i,k+1}^{n}-w_{i,k-1}^{n})-\frac{\Delta t}{\Delta z}w_{0}(\rho_{i,k+1}^{n}-\rho_{i,k-1}^{n}) \quad . \quad \text{....(6)}$$

Momentum conservation equation (Eq.2) reduces to Eq.7 because there is a change of mass flow due to changes in the length and depth of the basin, hydrostatic force, advection force

$$\left(\frac{\partial \rho U}{\partial t}+\frac{\partial \rho u U}{\partial x}+\frac{\partial \rho w U}{\partial z}\right)-(Po+\rho.g.h)\Delta z.\Delta y-\mu\frac{U.B}{\Delta x}=0 \quad \text{....(7)}$$

Because of the influence of velocity direction, then Eq. 7 is converted into Eq. 8, ie the momentum equation on the x axis (long basin).

$$\rho\left(\frac{\partial u}{\partial t}+w\frac{\partial u}{\partial z}+u\frac{\partial u}{\partial x}\right)+u.q-(Po+\rho.g.h)\Delta z.\Delta y-\mu\frac{u.\Delta z}{\Delta x}=0 \quad \text{....(8)}$$

With the application Leap Frog method, then Eq. 8 is converted into Eq.9

$$u_{i,k}^{n+1}=u_{i,k}^{n-1}-\frac{\Delta t}{\Delta x}u_{i,k}^{n}(u_{i+1,k}^{n}-u_{i-1,k}^{n})-\frac{\Delta t}{\Delta z}w_{i,k}^{n}(u_{i,k+1}^{n}-u_{i,k-1}^{n})+$$
$$\frac{2\Delta t}{\rho_{i,k}^{n}}[((Po+\rho.g.h)\Delta z.\Delta y)+(\mu\frac{u_{i,k}^{n}.\Delta z}{\Delta x})-(u_{i,k}^{n}.q_{i,k}^{n})] \quad \text{....(9)}$$

Based on non-linear stability analysis then transformed into Eq.10.

$$u_{i,k}^{n+1}=u_{i,k}^{n-1}-\frac{\Delta t}{\Delta x}u_{0}(u_{i+1,k}^{n}-u_{i-1,k}^{n})-\frac{\Delta t}{\Delta z}w_{0}(u_{i+1,k}^{n}-u_{i-1,k}^{n})+$$
$$\frac{2\Delta t}{\rho_{0}}[((Po+\rho.g.h)\Delta z.\Delta y)+(\mu\frac{u_{0}.\Delta z}{\Delta x})-(u_{0}.q_{0})] \quad \text{...(10)}$$

Eq.7 was changed to Eq.11, namely the momentum equation on the z axis (depth basin).

$$\rho\left(\frac{\partial w}{\partial t}+u\frac{\partial w}{\partial x}+w\frac{\partial w}{\partial z}\right)+w.q-(Po+\rho.g.h)\Delta z.\Delta y-\mu.w=0 \text{...(11)}$$

With the application Leap Frog method, then Eq.11 to Eq.12

$$u_{i,k}^{n+1}=u_{i,k}^{n-1}-\frac{\Delta t}{\Delta x}u_{i,k}^{n}(w_{i+1,k}^{n}-w_{i-1,k}^{n})-\frac{\Delta t}{\Delta z}w_{i,k}^{n}(w_{i,k+1}^{n}-w_{i,k-1}^{n})+$$
$$\frac{2\Delta t}{\rho_{i,k}^{n}}[((Po+\rho.g.h)\Delta z.\Delta y)+(\mu.w_{i,k}^{n})-(w_{i,k}^{n}.q_{i,k}^{n})] \quad \text{.....(12)}$$

Based on non-linear stability analysis then transformed into Eq.13.

$$u_{i,k}^{n+1}=u_{i,k}^{n-1}-\frac{\Delta t}{\Delta x}u_{0}(w_{i+1,k}^{n}-w_{i-1,k}^{n})-\frac{\Delta t}{\Delta z}w_{0}(w_{i,k+1}^{n}-w_{i,k-1}^{n})+$$
$$\frac{2\Delta t}{\rho_{0}}[((Po+\rho.g.h)\Delta z.\Delta y)+(\mu.w_{0})-(w_{0}.q_{0})] \quad \text{...(13)}$$

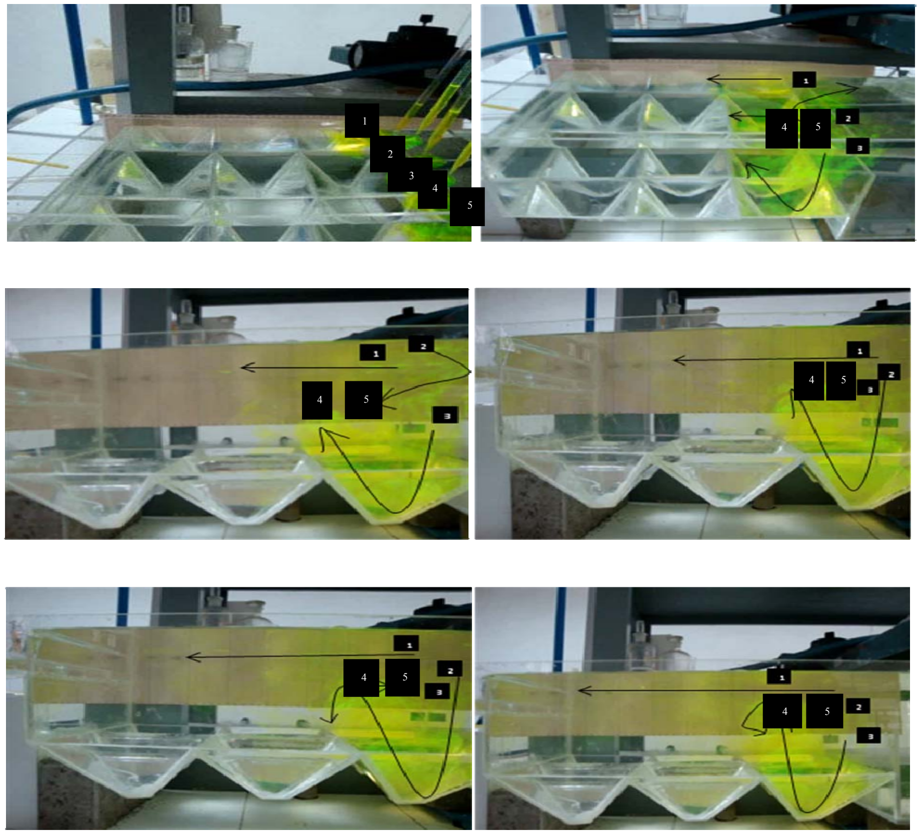

Figure 1. General flow pattern trends as a function of flow rate with dye evolution during a qualitative experiment, flow rate 15 ml/s, upper pass distributor, pictures taken every 10 s

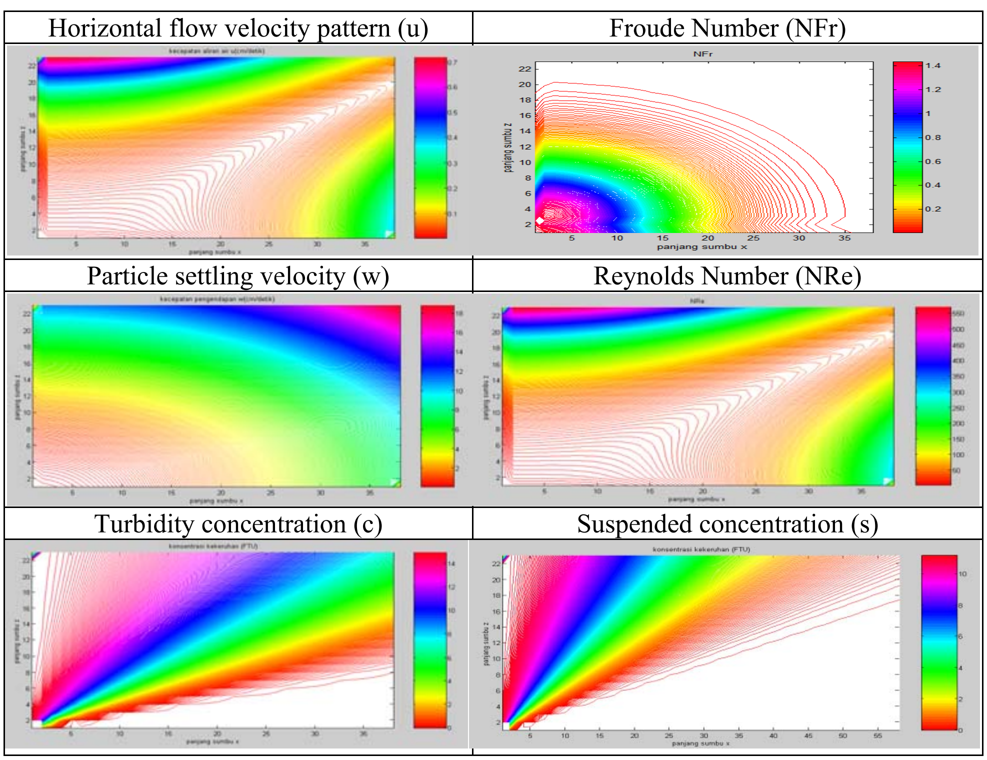

Figure 2. Visualization of mathlab program with flow rate 36 liters/hour and coagulant alum

Transport phenomena equations (Eq.3) reduces to Eq. 14 with the application Leap Frog Method.

$$C_{i,k}^{n+1} = \frac{\Delta t}{\Delta x} u_{i,k}^{n} (C_{i+1,k}^{n} - C_{i-1,k}^{n}) + \frac{\Delta t}{\Delta x} w_{i,k}^{n} (C_{i,k+1}^{n} - C_{i,k-1}^{n}) - C_{i,k}^{n-1} \quad ...(14)$$

Based on non-linear stability analysis then transformed into Eq.15.

$$C_{i,k}^{n+1} = \frac{\Delta t}{\Delta x} u_0 (C_{i+1,k}^{n} - C_{i-1,k}^{n}) + \frac{\Delta t}{\Delta x} w_0 (C_{i,k+1}^{n} - C_{i,k-1}^{n}) - C_{i,k}^{n-1} \quad ....(15)$$

Formulation of mathematical models of settling flocs in the sedimentation basin that is Eq.6, Eq.10, Eq.13, Eq.15 was visualized using Mathlab program.

4. Results and discussion

4.1 Identifications of pattern: After injecting the coloring with fluorescent, the veins in the tank may be observed. Figure 1 described schematically the observed paths with different flow rates. Every flow rates variation has the same flow pattern, but velocity was varying alongside basin. Flow at first (1st) point was tends to move faster than the others, a backward flow was observed at the second, third and fourth (2^{nd}, 3^{rd}, 4th) point, and a stagnant flow was observed at the fifth (5th) point. In the bottom section of the tank, the above is mentioned currents form. These currents touch the bottom, where a backwards flow was observed. In general, the upper pass distributor such this experimental device caused the formation of a main current, at depth for low flow rates and in the upper regions for high ones. Several return currents were also noticed.

Three flow rates were used, which was taken into account the transversal section of the tank, represented mean pass-through rates ranging from 0.98 cm/s – 0.05 cm/s. In previous works, other authors used rates of up to 1.72×10^{-1} m/s, but the usual values were below 1×10^{-2} m/s (Lopez, et.al.,2007). Anyway, NRe and NFr were the key parameters and it was their orders that were to be maintained. Since it was impossible to observe similarity according to both numbers at the same time, NFr was the most often considered, as it related to the inertia forces with the gravity forces (Ahmadi, et.al., 2007). Therefore minimum velocity rates was 0.25 cm/s so that NRe values < 2000 and NFr values > 1.10^{-5}, which was design criteria for settling flocs in sedimentation basin (Kantoush, et.al., 2008).

4.2 Implementation of mathemathical formulation: Physical model with length of basin=37.2 cm and depth = 12 cm is used to identify the flow pattern, flow velocity measurements and the identification of patterns of settling. From the results of running by using physical models derived data, namely the horizontal flow velocity data, the value of turbidity at the starting point or sedimentation basin inlet. The other data consists of: dimensional basin, detention time, flow rates, flow rates of runoff, velocity injection. While the particle settling velocity of 0.025 cm/sec-0.06 cm/sec for the average particle diameter of 0.08 mm-0.85 mm obtained from the research data in Malaysia. These data are input to run the model in Mathlab. Running the model for all points, it has 5 points on the inlet of the sedimentation tanks with various types of coagulant.

Output running HP2S model of horizontal flow velocity pattern (u), the pattern of particle settling velocity (w), the pattern of turbidity concentration (c) and suspended solid concentration as a parameter to analyze the deposition of flocs. Output from running model are NRe showing laminar flow conditions and NFr, which indicates stable flow conditions.

Based on the horizontal flow velocity measurements, obtained a linear relationship between horizontal flow velocity against NRe and the nonlinear relationship between horizontal flow velocity and NFr. The relationship will be strengthened through the precipitation pattern model by adding the influence of flocs concentration turbidity. Visualization images running the model shows that the coordinate (0,0) is the starting point or inlet sedimentation basin, where the x-axis represents the surface of the basin and the z axis is the depth. Visualization pictures show the settling zone starting from the inlet to the depth of the tub. Figure 2 is one of the results of running the model with the use of alum coagulant on flow rate 36 liters/hour.

Overall, the results of running with a variety of data showed settling flocs patterns in the sedimentation basin which explained that the zones of sedimentation (settling zone) starting from the inlet to the outlet there is a decrease of flow velocity pattern, NRe, NFr and the concentration of turbidity. In addition, decrease also occurred along with the depth of the settling basin zone (Boyle, et.al., 2005). As for the pattern of settling flocs velocity there was an increase from the inlet to the outlet and along with the depth of the basin.

4.3. Simulation model using Matlab: Simulation HP2S model in settling zone boundary used only on the certain of horizontal flow velocity, Reynolds number, Froude number and turbidity, retention times and depth of basin. It was happened because of influenced of a shear force, which fluid flow movement in each layer would be experience of mixing between layer in small scale and would be generated tension force then kinetic energy decreased (Van der Walt, 2008). While settling flocs velocity became increased in simulation. The particle settling velocity was decreased with increased of turbulence intensity, but this tendency diminished when diameter got smaller that might be due to that the smaller particles settled down slowly for they were influenced more by turbulence than gravitation. When particle diameter was smaller enough, the particle was tends to suspended and hardly to settled, no matter how intense the turbulence was (Guo et.al., 2009).

Figure 2 showed simulation of HPAs model with length basin variation to ensure that hydrodynamic conditions has same pattern to length basin constant. Behavior of hydrodynamics in rectangular settling basin was influenced by kinetic energy, which the biggest was on surface basin and dissipated along with length and depth of sedimentation basin. Therefore, velocity became decrease and particles were heavier than water were tend to sink to the bottom of the tank thereby dragging fluid along. The movement of fluid in turn affected to the settling of particles. It was mean that NRe, NFr, turbidity was decreased and settling velocity was increased. Based on simulation model experimental, minimum velocity rate was 0.52 cm/s with NRe values < 2000 and NFr values > 1.10^{-5} could removed turbidity 37.5% until 87.5% as initial value removal with various coagulants types.

Formulation of mathematical model of flocs precipitation patterns developed from HAs model can be set in rectangular sedimentation tanks by using the parameters of the flow velocity pattern, the pattern of deposition velocity and concentration patterns of turbidity, Reynolds Numbers and Froude Numbers partially. Formulation of mathematical models of flocs precipitation patterns is still limited to the hydrodynamic model and settling flocs velocity model and flocculation model. Behavior of hydrodynamics in rectangular settling basin was influenced by kinetic energy. The biggest energy is on surface basin and dissipated along with length and depth of sedimentation basin. Implementation of the HPAs model still in laboratory scale and the research will continue to validate the model by using pilot scale implementation, such as in water works.

ACKNOWLEDGEMENT

This research was granted by Directory of Research and Community Service, Ministry of National Educational Republic of Indonesia No. 097/ SP2H/ PL/ Dit.Litabmas/ III/ 2012

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