Environ. Eng. Res. Vol. 10, No. 1, pp. 15~21, 2005
Korean Society of Environmental Engineers

NUMERICAL STUDY FOR A SECONDARY CIRCULAR CLARIFIER WITH DENSITY EFFECT

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(received September 2004, accepted February 2005)

Abstract : A computer program is developed for the prediction of the flow pattern and the removal efficiency of suspended solid (SS) in a circular secondary clarifier. In this study the increased density effect by SS on hydrodynamics has been systematically investigated in terms of Froude Number (*Fr*), baffle existence, and a couple of important empirical models associated with the particle settling and Reynolds stresses. A control-volume based-finite difference method by Patankar is employed together with the SIMPLEC algorithm for the resolution of pressure-velocity coupling. The k-ε turbulence and its modified version are incorporated for the evaluation of Reynolds stresses. The calculation results predicts well the overall flow pattern such as the waterfall phenomenon at the front end of the clarifier and the bottom density current with the formation of strong recirculation especially for the case of decrease of *Fr*. Even if there are some noticeable differences in the prediction of two turbulence models, the calculated results of the radial velocity profiles are generally in good agreement against experimental data appeared in open literature. Parametric investigation has been systematically made with the *Fr* and baffle condition with detailed analysis.

Key Words : Suspended solid, Froude number, waterfall phenomenon, bottom density current

INTRODUCTION

Settling by gravity is the most common and extensively applied treatment process for the removal of suspended solids (SS) from the water and wastewater. Since the investment for settling tanks in treatment plants is high as about 30% of the total investment, the calculation of the SS removal efficiency has been the subject of numerous theoretical and experimental studies.[1) The performance of clarifier depends on the characteristics of the SS (particle size, density, settling velocity, and concentration), the flow field (inlet flow velocity, turbulence intensity), and the geometrical dimension of clarifier with the baffle. Especially the calculation of flow in the secondary clarifiers is difficult problem due to the strong buoyancy effect of density variation by the increased concentration of SS. The increased density gives rise to a couple of characteristic flow feature such as density waterfall phenomenon near the inlet of the clarifier and solid cascading phenomenon in the clarification of suspended solids especially for the low Froude number (*Fr*) situations.

Therefore, in this study, the flow pattern is

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investigated numerically by the use of computer program developed to figure out the hydrodynamic characteristics. However, most models presented in the literature have been restricted to primary clarifiers with relatively low concentrations operating in a neutral density environment.[2,3] But this kind of model is not quite appropriate to predict the behavior of the sediment induced density currents in a secondary clarifier with high SS concentration. Some important behavior of density flow in secondary clarifier has not been investigated thoroughly. Even if there are some research efforts about this matter, the increased density effect on the performance of the second clarifier is not clearly understood due to the complicated flow pattern.[4~7]

Therefore the objective of this study is to formulate a reliable computer program to handle this particular problem using well-known algorithm and related models, which predicts the flow patterns and thereby to obtain a sound physical insight for a large range of densimetric *Fr* together with the important parameters such as baffle configuration, empirical models of SS settling and Reynolds stresses.

MODEL DEVELOPMENT

Governing Equation and Turbulence Model

The flow patterns for density-stratified fluids in a circular clarifier are usually different from those of a fluid with uniform density under the same boundary conditions. The relative importance of inertial and gravity forces in the settling tank can be characterized in terms of the inlet momentum and buoyancy flux defined by a similarity criterion, *Fr*.

$$Fr = \left[u_0^{\,2} \, / \, \frac{gH_{in}(\rho - \rho_r)}{\rho_r} \right]^{1/2} \qquad (1)$$

in which ρ_r = the reference density (clean water). The value of ρ is the local density of mixture; u_0 = influent velocity; and H_{in} = depth of influent stream.

A computer model for the resolution of stratified flow consists of a set of conservation equations for continuity and momentum, turbulent kinetic energy k, dissipation of turbulence energy ε and solids concentration.[8] These can be expressed as

$$\frac{\partial(\rho\phi)}{\partial t} + \frac{\partial}{\partial x_j}(\rho \vec{u}_j \phi) = \frac{\partial}{\partial x_j}(\Gamma_\phi \frac{\partial \phi}{\partial x_j}) + S_\phi \qquad (2)$$

where ϕ denotes general dependent variables expressed as a physical quantity per unit mass. Further, u, v, ρ, Γ_ϕ and S_ϕ stand for radial and vertical velocity components, density, turbulent diffusion coefficient and source term corresponding to ϕ, respectively. The radial u- and vertical v- momentum equations are shown in Eqn (3) and (4), where ν_t is kinetic turbulent eddy viscosity and $g(\rho - \rho_r / \rho)$ represents the gravitational force, which account for density variation.

$$\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial r} + v\frac{\partial u}{\partial y} = -\frac{1}{\rho}\frac{\partial p}{\partial r} + \frac{1}{r}\frac{\partial}{\partial r}(r\nu_t \frac{\partial u}{\partial r}) + \frac{1}{r}\frac{\partial}{\partial y}(r\nu_t \frac{\partial u}{\partial y}) + S_u \qquad (3)$$

$$\frac{\partial v}{\partial t} + u\frac{\partial v}{\partial r} + v\frac{\partial v}{\partial y} = -\frac{1}{\rho}\frac{\partial p}{\partial y} + \frac{1}{r}\frac{\partial}{\partial r}(r\nu_t \frac{\partial v}{\partial r}) + \frac{1}{r}\frac{\partial}{\partial y}(r\nu_t \frac{\partial v}{\partial y}) + g\frac{\rho - \rho_r}{\rho} + S_v \qquad (4)$$

where $S_u = \frac{1}{r}\frac{\partial}{\partial r}(r\nu_t \frac{\partial u}{\partial r}) + \frac{1}{r}\frac{\partial}{\partial y}(r\nu_t \frac{\partial v}{\partial r}) - 2\frac{\nu_t}{r^2}u$ and

$$S_v = \frac{1}{r}\frac{\partial}{\partial r}(r\nu_t \frac{\partial u}{\partial y}) + \frac{1}{r}\frac{\partial}{\partial y}(r\nu_t \frac{\partial v}{\partial y})$$

The local fluid density is related empirically to the local values of suspended solid concentration by

$$\rho = \rho_r + C(1 - S_S^{-1}) \qquad (5)$$

where C = solid concentration and S_S = the empirical specific gravity of the solid particles. The concentration equation for suspended solids is

$$\frac{\partial C}{\partial t} + u\frac{\partial C_i}{\partial r} + v\frac{\partial C_i}{\partial y} = \frac{1}{r}\frac{\partial}{\partial r}(r\nu_{sx} \frac{\partial C_i}{\partial r}) + \frac{1}{r}\frac{\partial}{\partial y}(r\nu_{sy} \frac{\partial C_i}{\partial y} + rVsC_i) \qquad (6)$$

in which v_{sx} and v_{sy} are eddy diffusivity of suspended solids in the r- and y-direction and V_s is particle settling velocity defined positively downward.

Proper modeling of settling characteristics of suspended solids has been one of the key processes to accurately predict the removal efficiency since SS concentration in a secondary clarifier typically varies from high values of the inlet suspension to low values of the clarified effluent. A large number of empirical formulas have been proposed to describe the relationship between solids concentration and solids settling velocity.[9] The mass settling equation by Takacs et al. (1991) appears at the present time to be the overall description of suspension behavior in secondary clarifiers but has some drawbacks for the regions of low concentration.[10] In this study, settling velocity is calculated with an empirical discrete settling model. The settling velocity of particle is dependent on particle size, showing that the larger particle shows up the higher settling velocity. Four particle groups with 0.15 mm, 0.35 mm, 0.65 mm, and 1.4 mm diameter are selected to evaluate the settling characteristics of SS inside a clarifier.

The eddy viscosity is calculated from the standard and RNG k-ε turbulence models which relates to the turbulence kinetic energy of k and the turbulence dissipation rate of ε.[11]

Boundary Conditions

An ideal tank geometry of a center-fed circular clarifier with a peripheral weir is used; the inlet is at the top of the tank and a tank depth of 5.5 m and a tank radius of 12.5 m is assumed as shown in Figure 1.

A uniform, parallel inlet flow is imposed with radial velocity of u_0 and vertical velocity v=0. The turbulence energy level is assumed with specified values of $k=0.1u_0^2$ and $\varepsilon = C_\mu^{3/4}(k^{3/2}/l_m)$. The inlet SS loading is assumed to be in a well-mixed state with dimensionless concentration unit. The water surface is modeled as a symmetric plane where the vertical velocity *v* and the normal gradients of velocity component *u* and *k* are set to zero. For ε and concentration C, empirical boundary conditions are used. The more details of the boundary conditions are presented elsewhere.[5,12]

Numerical Method

Two different meshes (12×22, 24×42 with nonuniform spacing) are used for the settling tank geometry (L/H=2.27). The SIMPLEC (semi-implicit method for pressure-link consistent equations) algorithm, with a power-law difference scheme presented by Patankar, is applied for the pressure-linked momentum equation.[8] Eqn (7) shows the general discretized form for the above governing Eqn (2).

$$a_p\phi_p = a_E\phi_E + a_W\phi_W + a_N\phi_N + a_S\phi_S + b \qquad (7)$$

where a_E, a_W, a_N, a_S, and a_P are coefficients

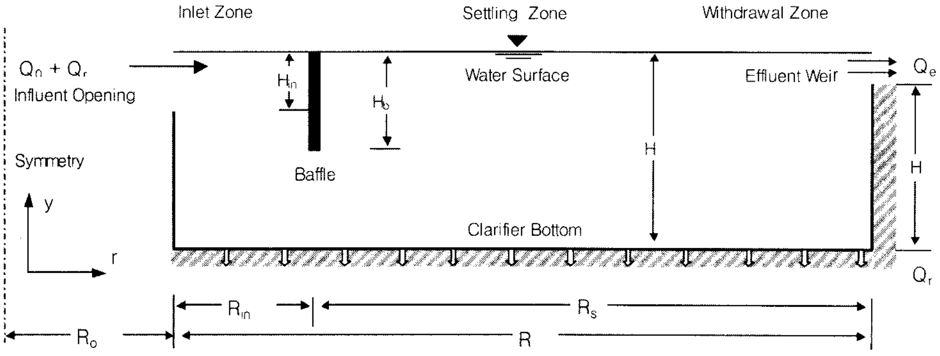


Figure 1. Schematic of a circular secondary clarifier.

of east, west, north, south and main grid nodes.

Eqn (7) is solved iteratively due to the nonlinear feature of the implicit equation with the use of line-by-line TDMA. Steady state solution for fluid flow is obtained starting from initially guessed value. The flow and solid transport equation coupled in the densimetric source term are simultaneously calculated in every iterative process.

CALCULATION RESULTS AND DISCUSSION

Increased Density Effect by SS

The flow field is affected by the hydraulic characteristics and SS concentration. Figure 2 and 3 show the density effect caused by the increased SS inlet loading. The influent flow for neutral density situations shown in Figure 2, after impinging on the reaction baffle, is deflected strongly downward. The downward current impinges on the tank bottom below the reaction baffle and then goes upward and forms a weak separation region behind baffle. Therefore, calculation without buoyancy showed a relatively unidirectional, plug-type flow throughout the tank under the region of the baffle.

Considering the density effect as shown in Figure 3, the horizontal inlet flow does not reach the flow - control baffle with relatively weak inertial effect, but plunges down toward the tank bottom as a density waterfall due to the low *Fr*, which corresponds to the high inlet water density and low inlet velocity. Under the submerged lip of the baffle, a strong counter flow re-entered the inlet zone to provide for the entrainment of clear ambient fluid due to the density waterfall. This means that in the case of increased density there exists a strong bottom recirculation flow, which does not appear for the neutral density condition as in Figure 2.

Turbulence Model Comparison

Figure 4 and 5 show the comparison of predicted velocity profiles by standard and RNG k - ε models against the experimental data measured in 1/12 physical scale model to the prototype.

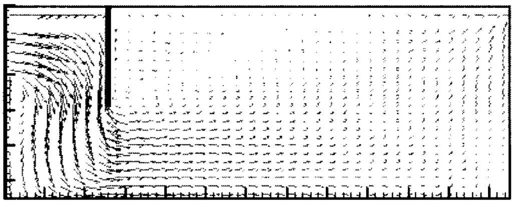


Figure 2. Streamline of the circular secondary clarifier for the neutral density condition.

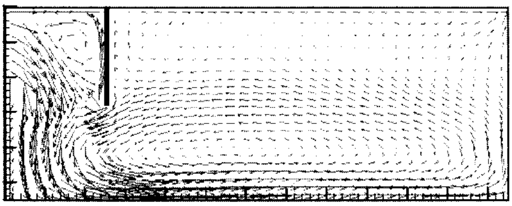


Figure 3. Streamline of the circular secondary clarifier with density effect (*Fr* = 0.078).

The experimental test is briefly summarized as follows.[13] Dye is injected into the influent to allow flow visualization. Experimental observations are recorded by side-view photographs and video tape through transparent walls. Small dye clouds are released from a point source into the flow immediately downstream of the baffle to measure the counter-velocity under the baffle lip. The movement of the dye clouds is recorded by a video camera, which is analyzed for the time displacement characteristics of the dye clouds. The dye clouds, from 0.5 to 2.5 sec after their release, are used to obtain the horizontal velocity components.[13]

Both predictions are, in general, in a fairly good agreement with the measurements at the upstream and center sections but somewhat differs from field data as gone to the clarifier bottom. This is partly caused by the approximate field measurements (error about 20%) and the limit of present model which relates to the 3-dimensional eddies.[14,15]

Standard k-ε model is commonly applied to the closure of Reynolds stresses term in the governing equation. It has been widely used for many industrially relevant flows but it has poor performance in flows with large extra strains,

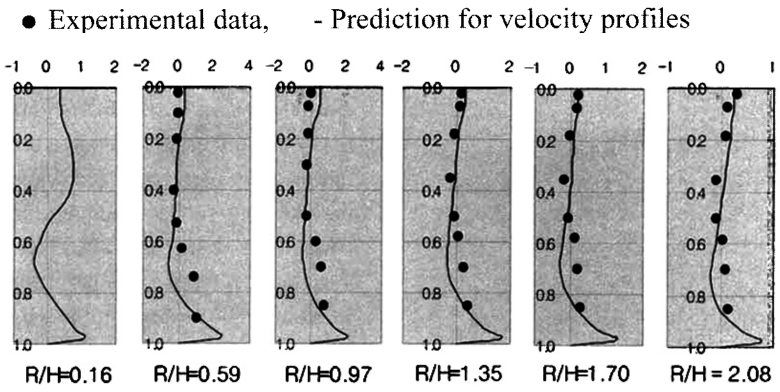


Figure 4. Comparison of predicted radial velocity profiles ($Fr = 0.34$) with data of scale model at various radial locations (standard k-ε model).

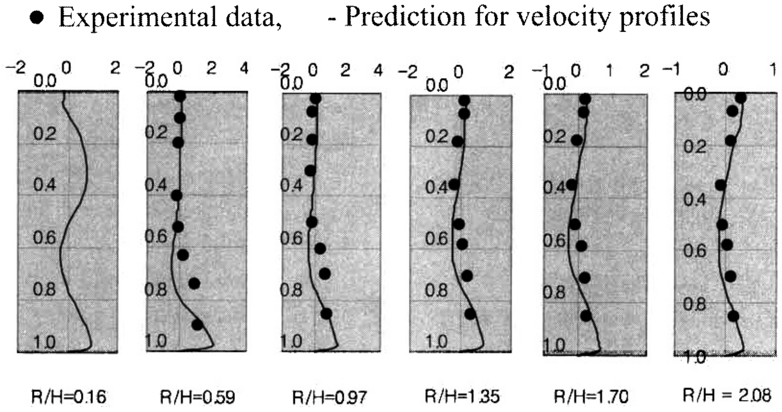


Figure 5. Comparison of predicted radial velocity profiles ($Fr = 0.34$) with data of scale model at various radial locations (RNG k-ε model).

rotating flows and strong buoyancy effects. To overcome this shortage, renormalized group (RNG) k-ε model is used. Figure 5 predicts better the separated flows than Figure 4 with standard k-ε model. And the sharpest bottom current found in Figure 4 is also disappeared because of viscosity modification near the wall in RNG k-ε model.[11]

Froude Number (*Fr*) Effect on Hydrodynamics

Figure 6 shows the normalized bottom density currents in the direction of radial coordinate as a function of the *Fr*. The total flow in the bottom density current is determined by integrating the horizontal velocity profiles from the clarifier bottom to the lower place of the recirculation zone. For low *Fr*, the greatest entrainment occurs in the inlet zone near the entrance. It is also noted that the lower the value of *Fr*, the greater is the strength of bottom current relative to the inflow. This is because the lower *Fr* gives rise to a stronger downward velocity which entrains more flow due to the lower pressure of this region.

Figure 7 shows the normalized upward flow rate in the downstream zone of the clarifier as a function of vertical position from the bed and *Fr*. The local upward flow rate increases with decreasing *Fr*, which is similar to the trend of Figure 6. It is expected that already settled solid or slowly settling floc can be forced upward in the withdrawal zone for low *Fr* flows.

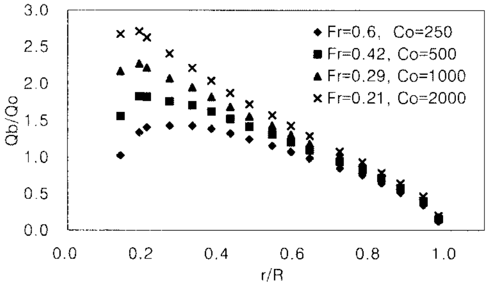


Figure 6. Strength of bottom density current in the withdrawal zone for different *Fr*.

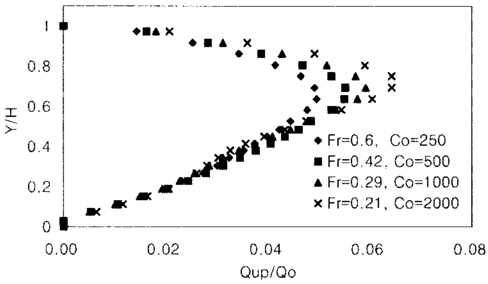


Figure 7. Strength of local upward flow in the withdrawal zone for different *Fr*.

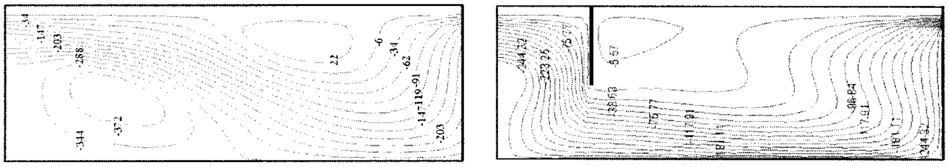
Baffle Effect on Flow Pattern

The streamlines with the existence of baffle are compared as shown in Figure 8. In case of high *Fr* flows without baffle, there is no settling zone. Hence, the introduced suspended solids directly go away through the clarifier with no chance of settling likewise Figure 8(a). Installation of baffle in the inlet zone can prevent the direct surface flow to outlet and increase the solid removal efficiency from 20% to 70% for high *Fr* flows. When a inlet concentration of suspended solids is high and a inlet velocity is low, that is low *Fr* flows, distinct phenomena are found in each section, where density waterfall in the inlet zone and large recirculation in the settling zone and upward flow in the withdrawal zone are observed in Figure 8(b). The flow patterns and performances of clarifier in low *Fr* flows are similar regardless of baffle. But the entrainment compensating flow is significantly reduced with the help of baffle.[12]

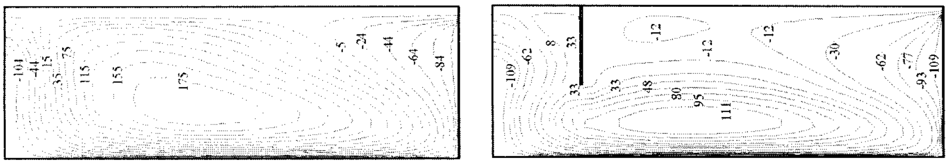
CONCLUSION

A series of systematic numerical calculations have been made using a computer program developed to investigate the performance of a secondary circular clarifier under the influence of density current by SS. Based on the this study, a number of useful conclusions can be drawn as follows;

The calculation results predicts well the overall flow pattern such as the waterfall phenomenon at the front end of the clarifier and the bottom density current due to the increased density effect especially for the case of decreased *Fr*. Further the calculated results of the radial velocity profiles with two turbulence models are generally in good agreement with experimental data in open literature. RNG k-ε



(a) Fr = 1.75



(b) *Fr* = 0.34

Figure 8. Comparison of streamlines as the installation of baffle.

model shows better prediction in the case of separated flow region but the direct comparison of two turbulence models is not made properly at this stage.

Parametric investigation has been systematically made with the *Fr* and baffle condition. For the case of low *Fr*, a strong bottom current is observed which does not need even the existence of baffle itself, while for the case of high *Fr*, the role of baffle such as location and height becomes more critical to induce a plug-type flow pattern for the increase of the removal efficiency and the prevention of SS re-suspension.

In general the program developed in this study shows the possibility as a viable tool to assist in the design and determination of optimal operating condition of a secondary clarifier.

ACKNOWLEDGMENT

This study was sponsored in part by the research fund of Core Environmental Technology Development Project for Next Generation sponsored by Ministry of Environment. The authors would like to thank for their assistance and financial support.

REFERENCES

1. Stamou, A. I., “Modelling of settling tanks - a critical review,” 3rd International Conference, Water Pollution 95, Porto Carras, Greece, 25-28 April (1995).
2. Zhou, S. and McCorquodale, J. A., “Influence of density on circular clarifiers with baffles,” *J. Environ. Eng.*, **118**(6), 829-847 (1992a).
3. Lee, E. J., Park, B. S., Jang, D. S., and Lee, S. I., “A numerical study on the design of primary clarifier:SS concentration and FTC,” *KSEE*, **18**(11), 1335-1346 (1996).
4. Zhou, S. and McCorquodale, J. A., “Modeling of rectangular settling tanks,” *Journal of hydraulic Engineering*, **118**(10), 1391-1405 (1992b).
5. McCorquodale, J. A. and Zhou, S., “Effect of hydraulic and solids loading on clarifier performance,” *Journal of hydraulic research*, **31**(4), 461-478 (1993).
6. Brouckaert, C. J. and Buckley, C. A., “The use of computational fluid dynamics for improving the design and operation of water and wastewater treatment plants,” *Water Sci. Technol.*, **40**(4-5), 81-89 (1999).
7. Kim, H. S., Shin, M. S., Jang, D. S., Jung, S. H., and Gang, D. H., “A study of SS-driven flow characteristics in a final clarifier,” *KSEE*, **26**(2), 629-634 (2004).
8. Patankar, S. V., Numerical heat transfer and fluid flow, McGraw-Hill Company (1980).
9. Mazzolani, G., Pirozzi, F., and d’Antonoi, G., “A generalized settling approach in the numerical modeling of sedimentation tanks,” *Water Sci. Technol.*, **38**(3), 95-102 (1998).
10. Takacs, I., Patry, G. G., and Nolasco, D., “A dynamic model of the clarification - thickening process,” *Water Res.*, **25**(10), 1263-1271 (1991).
11. Shin, M. S., Kim, H. S., Jang, D. S., Lee, Y. S., and Lee, S. N., “A numerical and experimental study on the mixing characteristics of stratified thermal storage,” *Environ. Eng. Res.*, **8**(1), 41-47 (2003).
12. Kim, H. S., "Numerical modeling of SS separation, thermal drying and incineration pollutant abatement in a sludge and wastes related combined system," Ph. D. Thesis, Chungnam National Univ. (2004).
13. McCorquodale, J. A. and Zhou, S., “Density currents in clarifiers,” Proc., 1987 Nat. Conf. Hydr. Engrg., *ASCE*, Williamsburg, Va., 56-61 (1989).
14. Lyn, D. A., Stamou, A. I., and Rodi, W., “Density currents and shear-induced flocculation in sedimentation tanks,” *Journal of hydraulic Engineering*, **118**(6), 849-867 (1992).
15. Shin, M. S., Kim, H. S., Jang, D. S., Kim, D. C., and Ohm, T. I., “Development of a computer progran for the prediction of SNCR process of a 2-D combustor,” *Environ. Eng. Res.*, **6**(1), 7-15 (2001).