# APPLICATION OF A CFD MODEL TO IMPROVE THE PERFORMANCE OF RECTANGULAR CLARIFIERS

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## ABSTRACT

There has been a long standing debate about the relative merits of circular and rectangular clarifiers. Both have been shown to be capable of excellent performance and both have experienced problems. The hydrodynamics of each configuration under similar hydraulic loading differ in fundamental aspects that determine what types of geometric modifications are likely to improve the clarifier performance. Griborio (2004), Griborio and McCorquodale (2005) and McCorquodale et al. (2005) presented the development and application of a computational fluid dynamics (CFD) model for predicting the performance of circular clarifiers under different geometric configurations. This paper uses a 2-D CFD model to investigate the response of a secondary rectangular settling tank to various internal modifications. Among the salient features of this model are: (1) discrete, zone and compression settling; (2) flocculation; (3) non-Newtonian flow; (4) floatable particles; (5) variable internal tank options including skirts and perforated baffles.

A simple rectangular tank with no special treatment was selected to demonstrate the response of rectangular tanks to different internal geometries. The selected clarifier is the Tomelilla secondary settling tank, which is describe by Larsen (1977). This tank was selected because performance data are available for model calibration, and because it represents a marginal performance case. After calibration, the model was used to evaluate different internal configurations. For the simulated trials, the best combination was an inlet skirt and an extended inboard launder with a perforated baffle.

## KEYWORDS

Rectangular settling tanks, clarifier model, hydrodynamics, computational fluid dynamics.

## INTRODUCTION

The relative merits of circular and rectangular clarifiers have been discussed for many decades. Both have been shown to be capable of excellent performance and both have experienced problems. Often the selection between rectangular and circular tanks is made on the basis of past experience and economic considerations such as maintenance costs and land costs. The hydrodynamics of each configuration under similar hydraulic loads differ in some fundamental aspects: a) the Reynolds Number in the circular center fed tank decreases significantly from the inlet to the launder while in the rectangular tank it remains more or less constant; b) the inlet zone in circular tanks is closer to 2 dimensional compared to the rectangular inlet; c) the sludge removal blade velocities are variable in the circular tank and constant in the rectangular tank; d) the aspect ratio of a typical rectangular tank (L/H) is much larger than the corresponding (R/H) in a circular tank; e) the floor slope in a circular tank with scrapers is generally larger than a rectangular tank. These factors will determine what type of geometric modifications will improve the clarifier performance and which will not be effective for each configuration. This paper uses a computational fluid dynamics (CFD) model to investigate the response of a secondary rectangular settling tank to various internal modifications. Among the salient features of the model are: (1) discrete, zone and compression settling; (2) flocculation; (3) non-Newtonian flow; (4) floatable particles; (5) variable internal tank options including skirts and perforated baffles. Details about the model characteristics are presented in McCorquodale et al. (2005).

## MODEL THEORY

This paper utilizes a model that solves a 2-D unsteady version of the stream function-vorticity equations with the density terms retained. A Smagorinsky type turbulence model is used with a Poisson Equation to determine the mixing length subject to a complete set of boundary conditions on the solid surfaces, free surface and open boundaries. Larsen (1977) showed that the pressure terms in the momentum equations can be eliminated by using the vorticity-stream function formulation. This method was selected because it guarantees fluid continuity. The vorticity $\omega$ is a measure of the rotational tendency of the fluid. The stream function formulation defines the two-dimensional flow field. The mean velocity component in the x- and y- directions can be obtained from the stream function $\psi$ using the following equations (Ji et al., 1996):

$$u = \frac{\partial \psi}{\partial y} \quad ; \quad v = -\frac{\partial \psi}{\partial x} \qquad 1$$

Combining Equation 1 with the definition of vorticity gives the field values of $\psi$,

$$\frac{\partial^2 \psi}{\partial x^2} + \frac{\partial^2 \psi}{\partial y^2} = -\omega \qquad 2$$

Using the vorticity definition and the 2-D assumption $\left[\frac{\partial(...)}{\partial z} \cong 0\right]$ the momentum equations in the x- and y- components are reduced to the following vorticity transport equation:

$$\frac{\partial \rho\omega}{\partial t} + \frac{\partial \rho u\omega}{\partial x} + \frac{\partial \rho v\omega}{\partial y} = \frac{\partial}{\partial x}\left(\rho r \nu_{eff} \frac{\partial \omega}{\partial x}\right) + \frac{\partial}{\partial y}\left(\rho \nu_{eff} \frac{\partial \omega}{\partial y}\right) + \rho \frac{\partial g'}{\partial x} + \hat{S}_{\omega} \qquad 3$$

where g'= $\frac{\rho - \rho_r}{\rho_r} g$ and $\hat{S}_{\omega}$ is a vorticity source term. The mixture density $\rho$ is related to the water reference density and suspended solids concentration through the following equation of state:

$$\rho = \rho_r + \left(\Sigma X_i - \Sigma[\frac{X_i}{S_{si}}]\right) \qquad 4$$

where $X_i$ is the suspended solids (SS) concentration for class i in mass per unit volume of mixture, and $S_{si}$ is the specific gravity of the dry solids for class *i*. The water reference density $\rho_r$ is a function of water temperature (*T*) and water dissolved solids content (TDS), e.g.

$\rho_r$ = [999.8396+18.224944 x *T* - 0.00792221 x $T^2$ - 55.4486 x $10^{-6}$ x $T^3$ + 14.97562 x $10^{-8}$ x $T^4$ –39.32952 x $10^{-11}$ x $T^5$ + (0.802-0.002 x *T*) x TDS] / [1+0.018159725 x T] 5

and the reference water viscosity is approximated by,

$$\nu_{ref} = \frac{(2.414\, x\, 10^{-5})}{\rho_r}\, x\, 10^{\left[\frac{247.8}{T+133.15}\right]} \qquad 6$$

where *T* is the water temperature in °C, $\rho_r$ is the water reference density in g/L, TDS is the total dissolved solids in g/L, and $\nu_{ref}$ is the water viscosity in ($m^2$/s). The Bokil model (Bokil, 1972) corrects the mixture kinematic viscosity for the effect of sludge concentration,

$$\nu = \nu_{ref} x 10^{-6}\ e^{1.386X} \qquad X \le 1 \text{ g/L}$$

$$\nu = 2.9 x \nu_{ref}\ e^{0.322X} \qquad X > 1 \text{ g/L} \qquad 7$$

in which *X* is SS in g/L and *v* is the mixture kinematic viscosity in $m^2$/s.

In the turbulent part of the flow,

$$\nu_t = G l_m^2 \qquad 8$$

where $l_m$ is the spatially variable mixing length and $G$ is defined as the mean gradient of the longitudinal and vertical velocities,

$$G = \sqrt{\left(\frac{\partial u}{\partial y}\right)^2 + \left(\frac{\partial v}{\partial x}\right)^2} \qquad 9$$

The $l_m$ field is obtained by means of a calibrated Poisson Equation; subject to appropriate boundary conditions, e.g. inlet mixing length and wall roughness,

$$\frac{\partial^2 l_m}{\partial x^2} + \frac{\partial^2 l_m}{\partial y^2} = \mathrm{K}_{l_m} \qquad 10$$

where $\mathrm{K}_{l_m}$ is a calibration constant.

To cover the complete range of laminar and turbulent flow, an effective viscosity $v_{eff}$ is introduced to combine the 'molecular-like' viscosity $v$ and the turbulent eddy viscosity $v_t$, i.e.

$$v_{eff} = v + v_t \qquad 11$$

Typical reported $S_s$ values for activated sludges range from 1.1 to 1.70 (e.g. Larsen, 1977). The advection-diffusion equation for solids transport is:

$$\frac{\partial \rho_i X_i}{\partial t} + \frac{\partial \rho_i u X_i}{\partial x} + \frac{\partial \rho_i v X_i}{\partial y} = \frac{\partial \rho_i v_{sx}}{\partial x}\frac{\partial X_i}{\partial x} + \frac{\partial \rho_i v_{sy}}{\partial y}\frac{\partial X_i}{\partial y} + \frac{\partial \rho_i V_{si} X_i}{\partial y} \qquad 12$$

Equation 12 is applied independently for each class of solids where $X_i$ is the concentration of Suspended Solids in C*lass i*; $v_{sx}$ and $v_{sy}$ are the eddy diffusivities of suspended solids in the x- and y- direction, respectively; and $V_{si}$ is the particle settling velocity for C*lass i*. Discrete settling is assumed up to a concentration of approximately 0.6 g/L. Zone settling is assumed with a single class for concentrations higher than 1.2 g/L; the zone settling is assumed to follow the Vesilind Equation. A transition zone between discrete and zone settling is applied for concentrations between 0.6 and 1.2 g/L. Table 1 summarizes the settling classes that were used in this model.

**Table 1 - Settling Regions Based on the TSS Concentration**

| Total Suspended Solids Concentration ($X$) | Settling Region | Settling Model |
|---|---|---|
| $X \leq$ FSS | Fine floc | Vs ~ O |
| FSS < $X \leq$ Discrete Threshold | Discrete settling | Individual floc settling velocity |
| Discrete Threshold < $X \leq$ Hindered Threshold | Flocculent settling | Transition zone |
| Hindered Threshold < $X$ ≤Compression Threshold | Hindered settling | Exponential model |
| X > Compression Threshold | Compression settling | Exponential model |

In this study the eddy diffusivity is defined as:

$$\nu_{sr} = \nu + \Gamma_r \nu_t \qquad 13$$

$$\nu_{sy} = \nu + \Gamma_y \nu_t \qquad 14$$

where $\Gamma_r$ and $\Gamma_y$ are the effective diffusion coefficients in the x- and y- directions respectively. The effective diffusion coefficients may be regarded as the inverse of the turbulent Prandtl-Schmidt numbers. In the case of density stratified flow with buoyant effects (when buoyancy dominates over kinetic energy), turbulence is subdued (this occurs basically in the vertical direction) and the diffusion coefficient of momentum and solids transport are reduced. Therefore, different Prandtl-Schmidt numbers should be used in the two directions. In the vertical direction a Munk-Anderson type damping function was applied to turbulent diffusivities in all the transport equations (including vorticity). The Prandtl-Schmidt in the horizontal was taken as 0.9.

Using the single-phase flow assumption (which implies that the volume occupied by the solids is negligible), the equations described above can be considered as the theoretical model to represent the major physical processes of solids movement (McCorquodale et al., 2004). Equations 1, 2 and 3 (continuity and momentum) and Equation 12 (mass transfer equation) can be described as a combination of an unsteady term (variation of the property with respect to time), two advective transport terms (describing the fluid-mass transfer process due to convection or flow movement in the plane), two terms related to the diffusion (mixing processes due to turbulent diffusion in two directions) and a source term (which usually extends the 'pure water' equation for the simulation of 'dirty water'). For example, Equation 3 includes a source term for the simulation of buoyancy effects and Equation 12 a term for the simulation of the particle settling process. Moreover, source terms are also used for the simulation of additional physical and biological processes, like flocculation or biological decay. In the case of 3D modeling the convection and diffusion terms are increased to 3 to indicate the space variation of the variables.

## METHODS

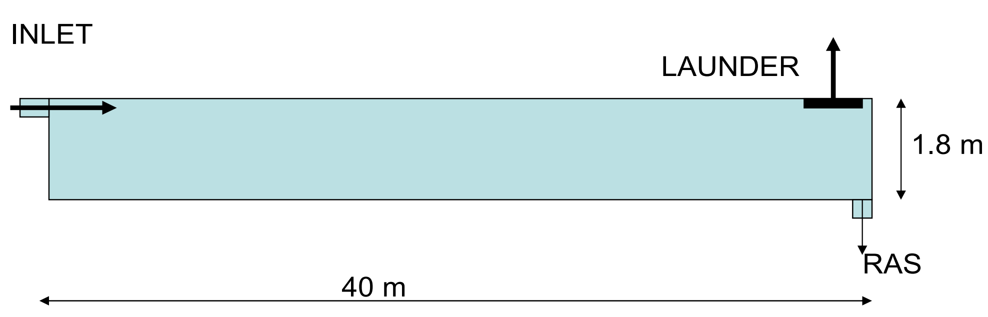
To demonstrate the response of the rectangular tank to different internal geometries, a base case of a simple rectangular tank with no special treatment was modeled. This case is based on the Tomelilla SST describe by Larsen (1977). This tank was selected because performance data are available for model calibration, and because it represents a marginal performance case. Table 2 shows the main tank dimensions and loadings. Figure 1 shows an idealized profile of the Tomelilla clarifier.

**Table 2 - Tomelilla SST's Geometry, Loading and Settling Properties Data**

| Geometry | Value | Discrete Settling Properties | Value |
|---|---|---|---|
| Tank Length | 40.0 m | Discrete Settling Threshold | 600 mg/L |
| Water Depth | 1.8 m | $V_{s1}$ | 12.00 m/h |
| Skirts | None | *Fraction 1 (Dimensionless)* | 0.80 |
| Bottom Slope | Flat Bottom | $V_{s2}$ | 5.25 m/h |
| Launder | Outboard (End Wall) | *Fraction 2 (Dimensionless)* | 0.15 |
| Withdrawal | End Wall | $V_{s3}$ | 1.20 m/h |
| **Loading** | **Value** | *Fraction 3 (Dimensionless)* | 0.05 |
| SOR | 0.68 m/h | **Zone Settling Properties** | **Value** |
| RAS Ratio | 0.5 | *Vmax* | 12.00 m/h |
| MLSS | 2200 mg/L | *K* | 0.5 L/g |

The model hydrodynamic parameters were calibrated before the model was applied. The data on velocities presented by Larsen (1977) were used to adjust the model bed roughness and vertical Prandtl-Schmidt number. Table 3 summarizes the modifications that were tested with the loading and settling properties given in Table 2.

**Figure 1 - Idealized Profile of the Tomelilla Clarifier**



## Table 3 - Performance Data for the Prototype and Modeled SSTs

| Data | Original SST | Inlet Skirt[(a)] | Inlet Skirt[(a)] + Perf. Baffle[(b)] | Inboard Launder[©] | Inlet Skirt[(a)]+ Inboard Launder[©] | Inlet Skirt[(a)]+ Perf. Baf.[(b)] + Inb. Launder[©] |
|---|---|---|---|---|---|---|
| ESS (mg/L) | 30.0 | 26.2 | 22.2 | 10.1 | 8.3 | ~ 4 |
| RAS SS | 6530 | 6540 | 6350 | 6570 | 6570 | 6370 |

[(a)] Skirt distance from inlet = 3 m; Skirt depth = 0.9 m

[(b)] Perforated Baffle distance from inlet =16 m; Gap above bed = 0.5 m; Height above bed = 1.8 m; Porosity = 50%
[©] Length of Launder = 18 m; End wall clearance = 1.8 m

## RESULTS AND DISCUSSION

Figures 4 to 9 illustrate the model simulated velocities and solids distributions for the modifications described in Table 3. The modeled effluent suspended solids (ESS) and return activated sludge (RAS) SS are summarized in Table 3. In general, for the base case, the predicted velocity field and SS profiles are in good agreement with the measured data presented by Larsen as indicated by Figures 2 and 3. These simulations demonstrate that the inboard placement of the launder in a rectangular SST is a major factor affecting the tank performance. The role of the inlet skirt is important in two aspects: 1) this baffle reduces the re-entrainment of already clarified liquid into the inlet zone, and 2) it provides a zone for flocculation. The perforated baffle interrupts the bottom density current and helps to redistribute the flow over the tank depth. However this type of baffle may create its own bottom current which then partially negates its positive effect. For these trials the best combination was an inlet skirt and an extended inboard launder with a perforated baffle.

## Figure 2 - Comparison of Measured and Modeled Velocity Profiles

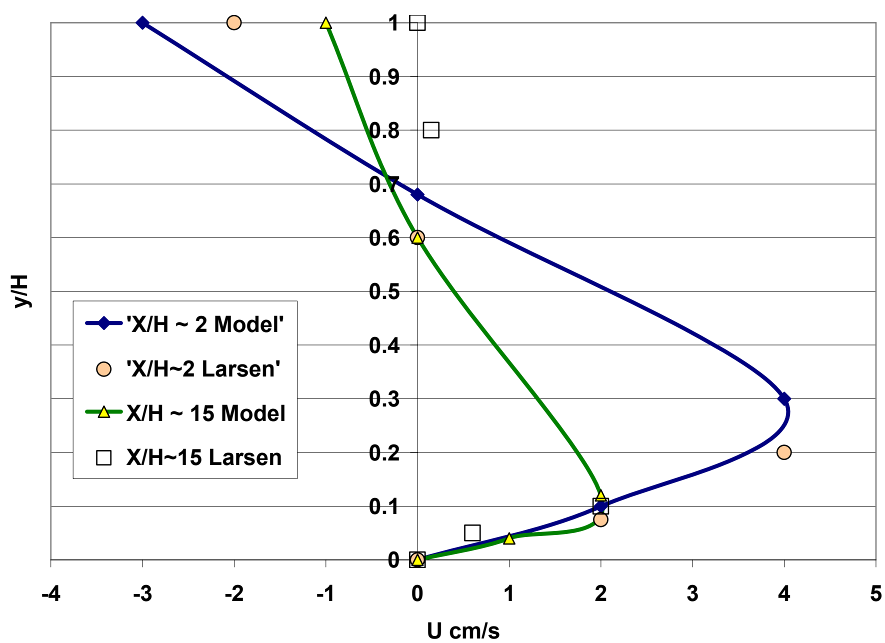


**Figure 3 - Comparison of Suspended Solids Measured by Larsen (1977) with 2-D Model Results**

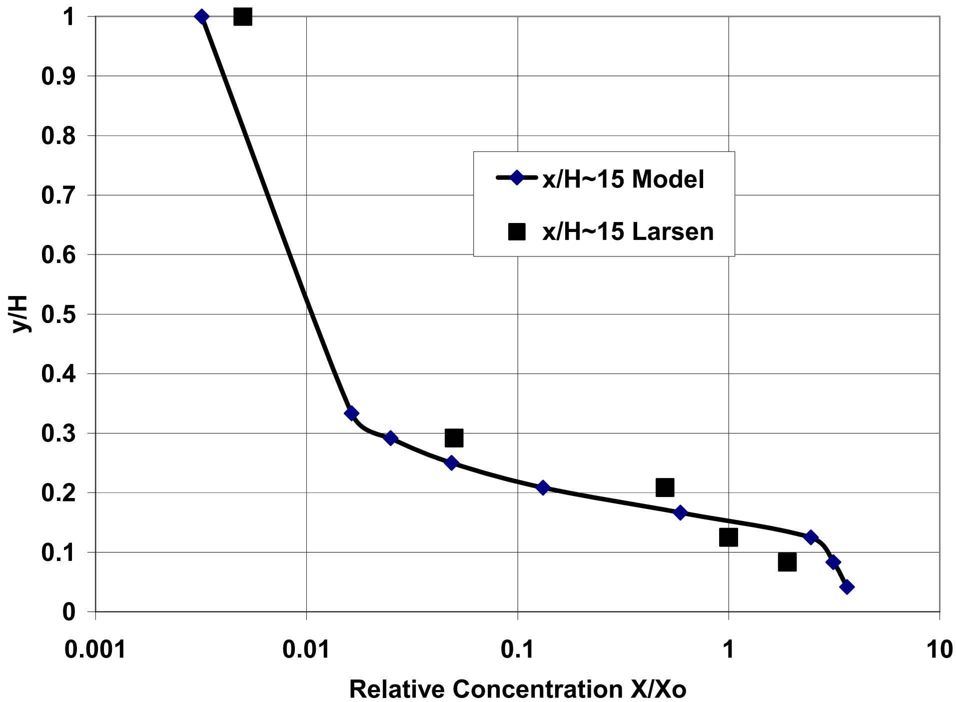



**Figure 4 - SS contours and Velocity Vector field of Tomelilla Secondary Clarifier (Basis of Comparison)**

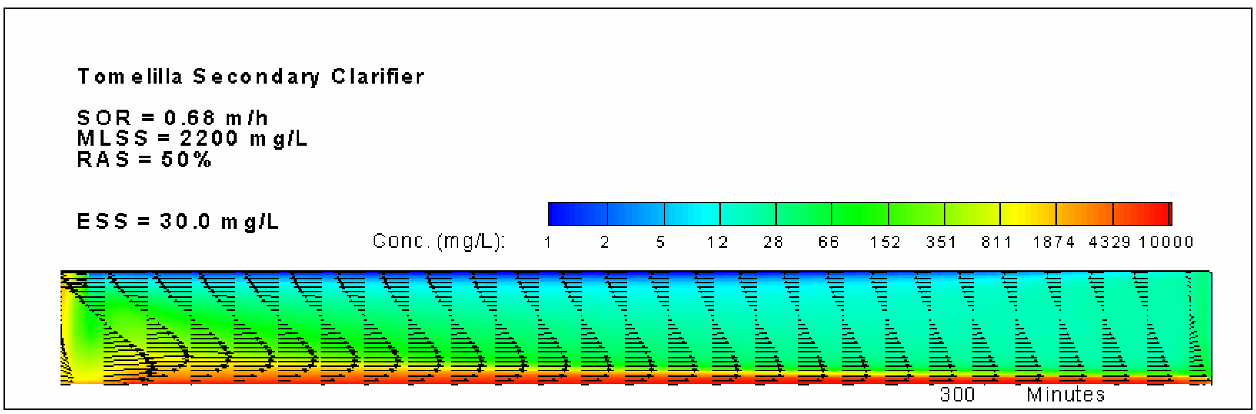


**Figure 5 - SS contours and Velocity Vector field of Modified Tomelilla Secondary Clarifier (Inlet Skirt)**

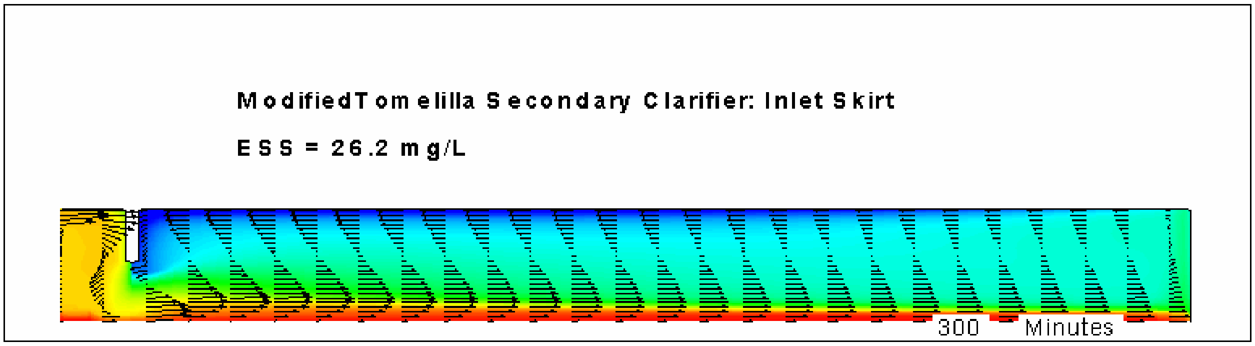



**Figure 6 - SS contours and Velocity Vector field of Modified Tomelilla Secondary Clarifier (Inlet Skirt + Perforated Baffle)**

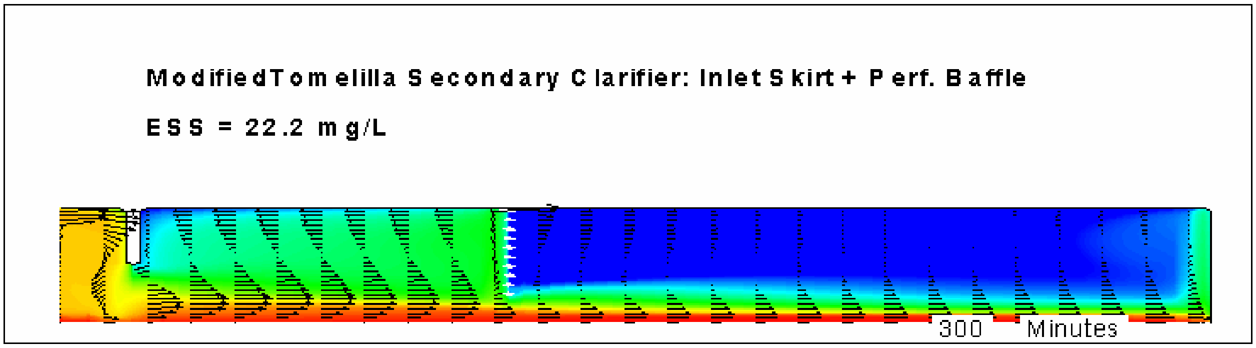



**Figure 7 - SS contours and Velocity Vector field of Modified Tomelilla Secondary Clarifier (Inboard Launder)**

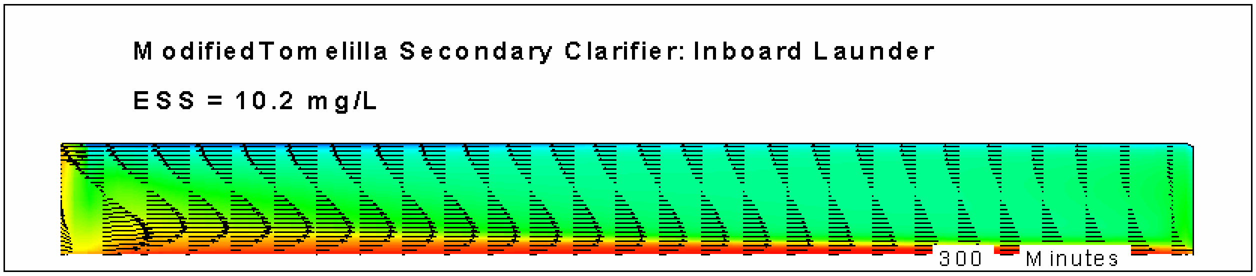


**Figure 8 - SS contours and Velocity Vector field of Tomelilla Secondary Clarifier (Inlet Skirt + Inboard Launder)**

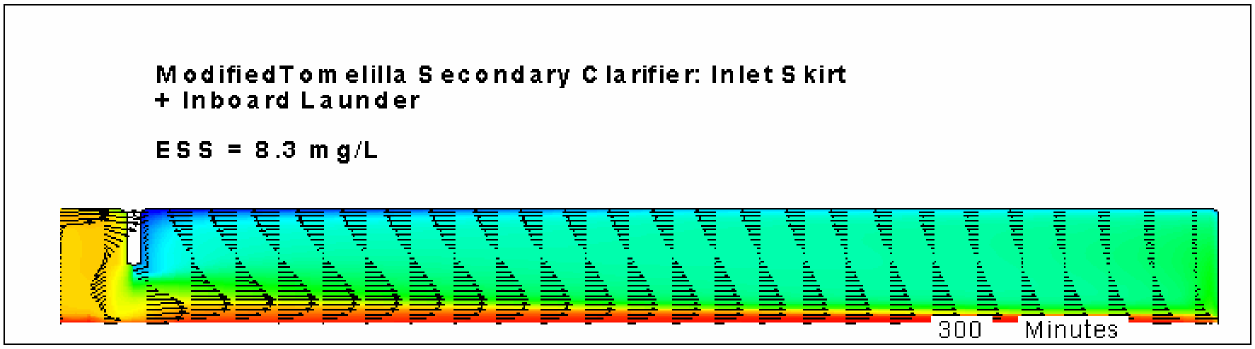
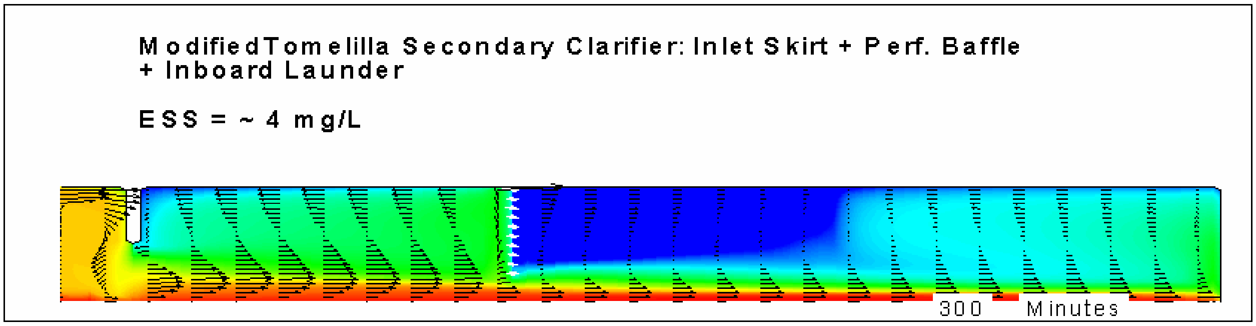



**Figure 9 - SS contours and Velocity Vector field of Tomelilla Secondary Clarifier (Inlet Skirt + Perforated Baffle + Inboard Launder)**




## CONCLUSIONS

A 2-D clarifier model was used to investigate the relative merits of several internal tank modifications. The installation of a flocculation zone skirt near the influent ports had a major benefit on the tank performance. The model showed that this benefit was due to the reduction in the re-entrainment of clarifier fluid into the MLSS and due to improved flocculation. The use of an extended inboard launder also produced a significant benefit in terms of reduced ESS. The use of a perforated baffle by itself was beneficial with or without the inlet skirt and the inboard launder. The best result was obtained by a combination of inlet skirt, inboard launder and a perforated baffle.

The work in this manuscript shows that CFD models can be used to optimize clarifier design and improve performance. A calibrated CFD model can serve as a numerical laboratory to test design concepts and considerations, and assess the benefits prior to full design and implementation of any proposed changes.

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