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Comparison of various settling velocity functions and non-Newtonian fluid models in circular secondary clarifiers

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Abstract−An axisymmetric single-phase model that predicts the sedimentation of activated sludge in a circular secondaryclarifier is developed. The k-ε turbulence model is used on a two-dimensional, orthogonal and stepwise grid. The concentration equation, which is extended to incorporate the sedimentation of activated sludge in the field of gravity, governs the mass transfer in the clarifier. The computational domain includes the sludge blanket where the viscosity is affected by the rheological behavior of the sludge. Results in case of non-Newtonian fluid model are compared with another numerical approach provided by Lakehal et al. Non-Newtonian fluid models--Bingham, Casson, and Herschel-Bulkley--are used. The influence of settling velocity functions and non-Newtonian models on the flow behavior isinvestigated. Finally, the best models are introduced and the ways that the non-Newtonian model introduces the plastic viscosity are discussed.

Key words: Turbulence, Secondary Clarifier, Settling Velocity Function, Activated Sludge, Non-Newtonian Fluid

INTRODUCTION

The secondary settling tank of an aerated sludge treatment plant represents a very important element in the process of removal of suspended solids. The first theory about the efficiency of settling tanks was developed by Hazen (1904) for individual particle settling in a uniform flow. Anderson (1945) discovered that the flow is far from uniform because of density stratification. The solids-loaded influent has a higher density than the ambient water and, hence, plunges as a density jet to the bottom of the tank; this is the so-called density current [1].

Early numerical modeling of flow in clarifiers by Schamber and Larock (1981) adopted the finite element technique together with the k-ε turbulence model and assumed pure water flow and a simplified inlet configuration at the surface. Imam et al. (1983) used a finite difference code with the constant eddy viscosity approach. Using a finite-volume code, Celik and Rodi (1985) applied the k-ε model to simulate the same experiment of Imam et al. approximating the settling properties of the suspension by a constant settling velocity. Some modeling studies were also made on the influence of buoyancy (e.g., DeVantier and Larock, 1987; Adams and Rodi, 1988; Zhou and McCorquodale, 1992) and flocculation (Lyn et al., 1992) on the flow and settling in final clarifiers. Krebs (1991) examined the influence of sludge removal on buoyancy affected flow and performed calculations of the flow in a rectangular tank including continuous flight scraper sludge removal against the main flow direction. The first attempt to model the flow in a radial section of a circular tank was due to DeVantier and Larock (1987), who used a finite element method and the k-ε turbulence model. These authors considered buoyancy and settling effects [2].

Numerical modeling of secondary clarifiers has gained an advanced state of development in the past years (Krebs, 1991; Lyn et al., 1992; Zhou and McCorquodale, 1992; Dahl et al., 1994; Szalai et al., 1994; Holthausen, 1995; Krebs et al., 1995). Corresponding measurements of concentration data are scarce however, full scale measurements of velocity distributions have been mainly conducted in rectangular secondary settling tanks (Larsen, 1977; Bretscher and Hager, 1990; Bretscher et al., 1992; Baumer et al., 1995; Uèberl, 1995) [3].

Recently, using a rheology function to account for the increased viscosity of highly concentrated sludge mixtures was performed by Lakehal et al. [4], DeClercq [1], McCorquodale et al. [5] and Weiss et al. [6], investigating flow of activated sludge in secondary clarifier.

The present study deals with density-affected flow in circular clarifiers. The geometry and the loading conditions (Fig. 1) are typical for tanks used in the Netherlands that is simulated by Lakehal et al. [4]. The clarifier is relatively shallow with only 2 m side-water depth. The bottom is inclined. The clarifier has two baffles: A vertical inlet baffle that forces the inflow to enter the tank at a relatively low position, and a horizontal deflection baffle that prevents short circuiting from the inlet to the sludge outlet. The region of the sludge blanket is included in the calculation domain and the bottom boundary is impervious. This approach allows the computation of the sludge blanket height and the concentration profiles within the sludge blanket. The influence of stratification on the turbulence properties is considered by means of sink terms in the equations of turbulent kinetic

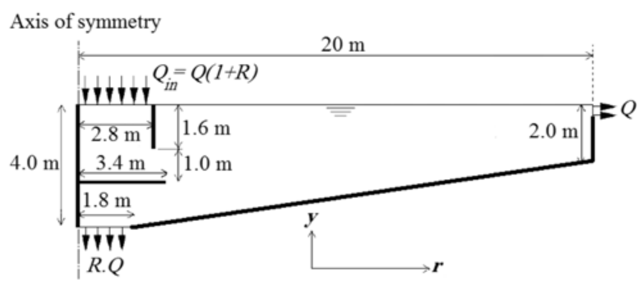

Fig. 1. The geometry of circular clarifier.

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energy. This type of flow was modeled by Lakehal et al. [4]. As compared to these studies, the present paper introduces the following changes.

- A CFD code is developed instead of using the FAST-2D software.
- Plastic viscosity term is added to the concentration diffusion equation.
- Orthogonal stepwise geometry is assumed to allow easy introduction of the inclined bottom. Similar feature was used by McCorquodale et al. [5], and McCorquodale et al. [7].
- The governing field equations are formulated by using the density of mixture and Boussinesq approximation is not used. The main difference is better satisfaction of continuity equation.
- New rheology functions–Casson, Herschel-Bulkley and modified Herschel-Bulkley--are used.
- New settling velocity functions based on experiments of DeClerck [1] and Weiss et al. [6] are used.

In present work, basic simulation results and sensitivity study on the influence of various settling velocity functions and non-Newtonian fluid models are investigated. Comparison of results in the case of a non-Newtonian fluid model will be performed using other numerical simulation, provided by Lakehal et al. [4]. The main objective of this study is to assess whether or not the settling velocity functions reported in the literature can be used along with a non-Newtonian fluid model. Settling velocity function and non-Newtonian fluid model largely depend on the sludge properties. In the present work, the sensitivity of concentration and velocity distribution on settling velocity functions and non-Newtonian fluid models are investigated. High sludge blanket height estimation of the clarifier surface leads to making a judgment about using a settling velocity function together with a non-Newtonian fluid model. Therefore, an appropriate settling velocity function together with a non-Newtonian fluid model can be introduced.

MATHEMATICAL MODEL

The flow field is obtained by solving the Reynolds-averaged Navier-Stokes equations in a cylindrical coordinate system. The k-ε model is used for turbulence modeling. The suspended sediment concentration is determined by solving a passive scalar equation, in which the particle settling velocity is introduced. The buoyancy effects that result from the sediment-induced density differences are accounted by considering a gravity sink term in the vertical momentum equation. Also, the damping influence of stratification on the production of turbulent kinetic energy is expressed as a sink term appearing in the transport equations of turbulent kinetic energy, k, and its rate of dissipation, ε.

1. Reynolds-averaged Navier-stokes Equations

The system of Reynolds-averaged Navier-Stokes equations for two-dimensional, axisymmetric, unsteady, density-stratified, and turbulent mean flow may be given as [4,6]:

$$\frac{\partial\rho}{\partial t}+\frac{\partial(\rho u)}{\partial r}+\frac{\partial(\rho v)}{\partial y}+\frac{\rho u}{r}=0 \tag{1}$$

$$\frac{\partial(\rho u)}{\partial t}+\frac{1}{r}\frac{\partial(r\rho uu)}{\partial r}+\frac{\partial(\rho uv)}{\partial y}=-\frac{\partial p}{\partial r}+\frac{1}{r}\frac{\partial}{\partial r}\left(r(\mu+\mu_t)\frac{\partial u}{\partial r}\right)+\frac{\partial}{\partial y}\left[(\mu+\mu_t)\frac{\partial u}{\partial y}\right]-\frac{\rho u}{r^2} \tag{2}$$

$$\frac{\partial(\rho v)}{\partial t}+\frac{1}{r}\frac{\partial(r\rho uv)}{\partial r}+\frac{\partial(\rho vv)}{\partial y}=-\frac{\partial p}{\partial y}+\frac{1}{r}\frac{\partial}{\partial r}\left[r(\mu+\mu_t)\frac{\partial v}{\partial r}\right]+\frac{\partial}{\partial y}\left((\mu+\mu_t)\frac{\partial v}{\partial y}\right)-\rho g \tag{3}$$

The equation of continuity is given by Eq. (1), and Eqs. (2), and (3), represent the r and y momentum conservation equations, respectively. The origin of the coordinate system is placed on the vertical center line, with the y-axis pointing vertically upwards from the bottom boundary. The field equations are given in terms of averaged flow variables, where u and v are the mean velocity components in the r (radial) and y (axial) directions, respectively. Also, t is the time, p is the pressure, ρ is the density of the mixture, g is the gravitational acceleration constant, μ is the viscosity of the sludge mixture, and μ_t is the turbulent viscosity. The governing field equations are formulated by using the density of mixture. So varying density of the sludge mixture is accounted for in all equation terms including density.

2. Standard k-ε Turbulence Model

The turbulent viscosity, μ_t, is determined by the turbulent kinetic energy, k, and also by the rate of dissipation of turbulence kinetic energy, ε, according to [1,4,8,9]:

$$\mu_t=\rho C_\mu\frac{k^2}{\varepsilon} \tag{4}$$

where C_μ=0.09 is a constant. The semi-empirical model, transport equations for k and ε may be given as:

$$\frac{\partial(\rho k)}{\partial t}+\frac{1}{r}\frac{\partial(r\rho uk)}{\partial r}+\frac{\partial(\rho vk)}{\partial y}=\frac{1}{r}\frac{\partial}{\partial r}\left[r\left(\mu+\frac{\mu_t}{\sigma_k}\right)\frac{\partial k}{\partial r}\right]+\frac{\partial}{\partial y}\left[\left(\mu+\frac{\mu_t}{\sigma_k}\right)\frac{\partial k}{\partial y}\right]+P+G-\rho\varepsilon \tag{5}$$

$$\frac{\partial(\rho\varepsilon)}{\partial t}+\frac{1}{r}\frac{\partial(r\rho u\varepsilon)}{\partial r}+\frac{\partial(\rho v\varepsilon)}{\partial y}=\frac{1}{r}\frac{\partial}{\partial r}\left(r\left(\mu+\frac{\mu_t}{\sigma_\varepsilon}\right)\frac{\partial\varepsilon}{\partial r}\right)+\frac{\partial}{\partial y}\left(\left(\mu+\frac{\mu_t}{\sigma_\varepsilon}\right)\frac{\partial\varepsilon}{\partial y}\right)+C_1\frac{\varepsilon}{k}(P+G-C_3G)-\rho_w C_2\frac{\varepsilon^2}{k} \tag{6}$$

where P is the generation of turbulence kinetic energy due to mean velocity gradients, that is, due to shear, and, G, corresponds to the generation of turbulence kinetic energy due to buoyancy.

$$P=\mu_t\left[2\left(\frac{\partial u}{\partial r}\right)^2+2\left(\frac{\partial v}{\partial y}\right)^2+2\left(\frac{u}{r}\right)^2+\left(\frac{\partial v}{\partial r}+\frac{\partial u}{\partial y}\right)^2\right] \tag{7}$$

$$G=-\left|\beta g\frac{\mu_t}{\rho\sigma_t}\frac{\partial\rho}{\partial y}\right| \tag{8}$$

In Eqs. (5), and (6), σ_k=1.0 and σ_ε=1.3 are the turbulent Prandtl numbers for k and ε, respectively. In Eq. (6), C_1=1.44 and C_2=1.92 are constants. The constant C_3 takes a value of 0.8-1.0 [1, 4]. In Eq. (8), σ_t=0.85 is the turbulent Prandtl number and β is the volume expansion factor introduced by Choi and Garcia [10]. Volume expansion factor is assumed to be unit here. For stably stratified flow simulation, μ_t in Eq. (8) is replaced with Eq. (4) and the coefficient of k is taken into the left side of numerical formulation and is not used as a source term.

3. Conservation of Mass in Turbulent Flows

The sludge transport equation for turbulent flow may be written as [4,6]:

Table 1. Various definitions of effective viscosity in concentration equations

No.	Definition		Ref.
1	$\mu_{er}=\mu_t/\sigma_r$ $\mu_{ey}=\mu_t/\sigma_y$	σ_r=0.7 σ_y=0.5-0.9	Lakehal et al. [4]
		σ_r=0.7 σ_y=0.7	Weiss et al. [6]
2	$\mu_{er}=(\mu+\mu_t)/\sigma_r$ $\mu_{ey}=(\mu+\mu_t)/\sigma_y$	σ_r=0.7 σ_y=0.7	DeClercq [1]
3	$\mu_{er}=\mu+\mu_t\Gamma_r$ $\mu_{ey}=\mu+\mu_t\Gamma_y$	Γ_r=0.2 Γ_y=10	McCorquodale et al. [5]
4	$\mu_{er}=\mu+\mu_t/\sigma_r$ $\mu_{ey}=\mu+\mu_t/\sigma_y$	σ_r=0.7 σ_y=0.5-0.9	Present simulation

$$\frac{\partial(\rho C)}{\partial t}+\frac{1}{r}\frac{\partial(r\rho uC)}{\partial r}+\frac{\partial(\rho vC)}{\partial y}$$
$$=\frac{1}{r}\frac{\partial}{\partial r}\left[r\mu_{er}\frac{\partial C}{\partial r}\right]+\frac{\partial}{\partial y}\left[\mu_{ey}\frac{\partial C}{\partial y}+V_sC\right] \tag{9}$$

where C is the concentration, and $V_s=V_s(C)$ is the settling velocity function. Also μ_{er}, μ_{ey} are the effective viscosity in r and y direction. Several definitions of effective viscosity can be found in the literature. These definitions and the definition used in the present simulation are presented in Table 1.

In Table 1, σ and Γ are the Schmidt number and diffusion coefficient, respectively, which may have different values in any direction. As noted by DeClercq [1], using a rheology function with yield stress means a large amount of viscosity in some region with low shear rate. This means high diffusivity in concentration equation and overestimation of blanket height. Lakehal et al. [4] and Wises et al. [6] remove the molecular viscosity from the diffusion coefficient of the concentration equation. This method cannot be accepted. Molecular viscosity in non-Newtonian fluids takes a high value (in some cases more than turbulence viscosity) and cannot be neglected. There is no considerable change between Newtonian and non-Newtonian fluid results when molecular viscosity is removed from concentration equations. In the present simulation, as shown in Table 1, an alternative definition of concentration diffusion that overcomes the above problems is used.

MIXTURE DENSITY

The equation of state links mixture density, ρ, to the concentration, C, of the suspended sludge:

$$\rho=\rho_w+\left(1-\frac{\rho_w}{\rho_s}\right)C \tag{10}$$

where ρ_w is the density of clear water, ρ is the local density of the mixture. According to the experiments of Larsen (1977), the density, ρ_s of the dry particles is assumed to be 1,450 kg/m^3 [4].

SETTLING VELOCITY

The settling velocity is expressed using the double-exponential function of Takacs et al. (1991), which is given by [1,4,6]:

$$V_s=V_0\left\lfloor e^{-r_p(C-C_{min})}-e^{-r_h(C-C_{min})}\right\rfloor \tag{11}$$

where V_0 (m/s) is a reference settling velocity, r_h and r_p (m^3/kg) induce the domination of the first and the second term in equation, for the falling and the rising part, respectively. According to Weiss et al. [6] the value for r_p is generally one order of magnitude larger than that of r_h. The constant C_{min}, is the concentration of non-settleable solids in the effluent of the clarifier.

In the activated sludge field the settling velocity of relative high concentration (in which particles settle as a unit at the same velocity independent of size) is usually measured in a batch test where the velocity of the sludge interface is measured directly. This value is commonly referred to as the zone settling velocity. The first term of Eq. (11) is for the simulation of the zone settling velocity, and the second term tries to simulate the effect of discrete particle settling at dilute concentrations [5].

BOUNDARY CONDITIONS

1. Inlet

At the clarifier inlet, the inlet concentration, C_{in}, in applied, which is equal to the concentration at the outlet of the aeration basin, and the inlet velocity components, u_{in} and v_{in} are used. The turbulence kinetic energy at the inlet, k_{in}, is calculated using $k_{in}=1.5\times(I_u v_{in})^2$ where I_u=0.224 is the turbulence intensity. Dissipation rate at the inlet, ε_{in}, is obtained from below equation:

$$\varepsilon_{in}=\frac{C_\mu^{3/4}k_{in}^{3/2}}{\kappa L_u} \tag{12}$$

where κ=0.4 is the von Karman constant. The turbulence length scale, $L_u=0.5\times R_{baffle}$, where R_{baffle} is the radius of the baffle skirt in the inlet region of the clarifier [4,6].

2. Free Surface

The vertical movement of the free surface of the clarifier is assumed to be negligibly small. This assumption simplifies the computation greatly, as it helps to keep the computational efforts to a minimum. The vertical (axial) velocity component is thus set to zero at the surface, v=0, and the horizontal (radial) velocity component, u, is computed assuming full slip, that is, the surface is treated as a stress-free entity.

3. Outlet

At the effluent outlet boundary, the values of the variables are extrapolated from computed near-outlet values. This extrapolation sets the stream-wise gradients to zero.

4. Wall

The no-slip condition must be obeyed at all solid boundaries, that is, u, v=0 at all clarifier walls. The boundary condition on the concentration is that the gradients perpendicular to all solid walls are set to zero, so that the solid walls are made impenetrable for the scalar species. Logarithmic wall functions are also applied to model the turbulent flow in the near-wall region of the clarifier.

RHEOLOGY OF ACTIVATED SLUDGE

The definition of shear stress is used for calculation the viscosity of activated sludge:

$$\mu_p = \frac{\tau_{xy}}{\dot{\gamma}} \tag{13}$$

where μ_p is the plastic viscosity that should be replaced with molecular viscosity in all equations, τ_{xy} is the shear stress of flow with individual definition in each model, and $\dot{\gamma}$ is the shear rate. According to Vradis and Protopapas [9], the shear rate may be defined as:

$$\dot{\gamma} = \sqrt{2\left(\frac{\partial u}{\partial r}\right)^2 + \left(\frac{\partial v}{\partial y}\right)^2 + 2\left(\frac{u}{r}\right)^2 + \left(\frac{\partial u}{\partial y} + \frac{\partial v}{\partial r}\right)^2} \tag{14}$$

Bingham Plastic, Herschel-Bulkley (pseudoplastic with yield stress), pseudoplastic and dilatant models may be defined for behavior of non-Newtonian fluids [1,12-14].

Another class of non-Newtonian fluids, the dilatant fluids, exhibit a behavior which is opposite to that of the pseudoplastic fluids. According to Behn (1960), this flow type does not appear in wastewater treatment [5]. A pseudoplastic flow with yield stress is called a Herschel-Bulkley fluid. In this respect, Monteiro (1997) performed a comparison between this and the Bingham model; a better fit with the Herschel-Bulkley model was obtained by DeClercq [1].

Although all mentioned models have been successfully fitted to rheological data, the appropriate model largely depends on the sludge properties, for instance, a yield stress is only observed at high solids concentrations. Other parameters such as the specific floc surface have been investigated as well (Dymaczewski et al., 1997), but the solids concentration appears to be the most important variable related to viscosity [1,4,6].

1. Bingham Model

According to the literature, one of non-Newtonian models that satisfy the behavior of activated sludge in secondary clarifier is the Bingham model [1,4,6]. In this case the applied stress needs to overcome some yield stress, τ_B, before a shear rate is induced in the fluid. The shear stress, τ_{ry}, can then be expressed as:

$$\tau_{ry} = \tau_B + \mu_B \dot{\gamma} \tag{15}$$

where τ_B is the Bingham yield stress and μ_B is the Bingham viscosity. Dahl (1993) used the plastic viscosity and the yield stress as fitting parameters to find agreement between experiments and numerical modeling of a pilot-scale clarifier fed with activated sludge [4]. The curve that was presented by Dahl for an inlet concentration of 4 g/L was approximated in this work by:

$$\mu_B = \mu_w + c_{pl} C^2 \tag{16}$$

where $c_{pl} = 2.473\times10^{-4}$ is constant and μ_w is the water viscosity. The yield stress, τ_B, was approximated with the function suggested by Dick and Ewing (1967):

$$\tau_B = \beta_1 \cdot \exp(\beta_2 C) \tag{17}$$

where, β_1 and β_2 are constants that are depending on the nature of the sludge. From the curve shown by Dahl (1993), the constants were approximated as $\beta_1 = 1.1\times10^{-4}$ kg/(m·s^2) and $\beta_2 = 0.98$ m^3/kg [4].

2. Herschel-Bulkley Model

Standard and modified Herschel-Bulkley models are presented in Eqs. (18), and (19), respectively. Modified Herschel-Bulkley model, is defined by DeClercq [1].

$$\mu_p = \frac{\tau_B}{\dot{\gamma}} + \mu_B \dot{\gamma}^{n-1} \tag{18}$$

$$\mu_p = \frac{\tau_B}{\dot{\gamma}}(1 - e^{-m\dot{\gamma}}) + \mu_B \dot{\gamma}^{n-1} \tag{19}$$

with

$$\tau_B = \beta_1 C^{\beta_2} \tag{20}$$

and

$$\mu_B = \mu_w + c_{pl} C^2 \tag{21}$$

where $\beta_1 = 9.0364\times10^{-4}$ kg/(m·s^2), $\beta_2 = 1.12$, m=169.47, n=0.7748, and $c_{pl} = 2.49338\times10^{-4}$ m^5/(kg·s^2) are equation constants.

3. Pseudoplastic Casson Model

The Casson equation for the sludge viscosity can be given as:

$$\mu_p = (K_1/\dot{\gamma}^{1/2} + K_2)^2 \tag{22}$$

where $\dot{\gamma}$ is the shear rate, K_1 the Casson yield stress parameter, and K_2 is the Casson viscosity parameter. Rheology experiments of Weiss et al. [6] show that K_1 depends quadratically on the concentration:

$$K_1 = AC^2 + BC \tag{23}$$

where A=0.00319 m$^{11/2}$kg$^{-3/2}$s^{-1}, and B=0.0146 m$^{5/2}$kg$^{-1/2}$s^{-1} are constant. The viscosity parameter, K_2, does not show a clear dependence on C and appears to be independent of the sludge concentration over the range of concentrations studied. Neglecting the yield stress parameter, K_1, Dollet (2000) found that K_2 does not depend on the sludge concentration, and gave a mean value of 0.032 kg$^{1/2}$ m$^{-1/2}$s$^{-1/2}$ for the Casson viscosity parameter. Both Dollet's observation on the concentration dependence of K_2 and his mean value for K_2 agree well with the results of Weiss et al. [6]. Thus according to Weiss et al. [6], it is assumed that K_2 is independent of the concentration for C≥C*=2 kgm^{-3} and is equal to the mean value of $K_{2,ave}$= 0.0436 kg$^{1/2}$m$^{-1/2}$s$^{-1/2}$. For the water viscosity value, μ_w, to emerge correctly as C→0, K_2 is assumed to depend linearly on the concentration on the interval 0≤C<C*. Thus, for C≥C*:

$$K_2 = K_{2,ave} \tag{24}$$

and for 0≤C<C*:

$$K_2 = \mu^{1/2} + \left(\frac{\overline{K}_2 - \mu^{1/2}}{C^*}\right) C \tag{25}$$

NUMERICAL SOLUTION AND RESULTS

A finite volume Staggered SIMPLEC (semi implicit method for pressure linked equations-corrected) code was provided using Intel Visual Fortran. For simplicity, 25 steps were used at the clarifier bottom for simulation the inclined bottom. The computational time step is Δt=0.5 s and the flow field will be steady after about 30,000 s. However, small waves will remain in the flow field even after steady state in some cases. Due to low quality of mesh using stepwise grid, finer grid dimension and better aspect ratio than Lakehal et al. [4] is used. The grid dimension 357×148 is used instead of 200×100. Two other grid dimensions also are used for mesh sensitivity analysis: 195×100, and 495×199. The grid independency is checked and illustrated in Fig. 2. This figure depicts the concentration profile at r=6 m for various grid sizes. Vertical axis, h/h_{max} is the non-dimensional height that is measured from the free surface. Using a grid dimension of 357×148 is appropriate. This grid independency is

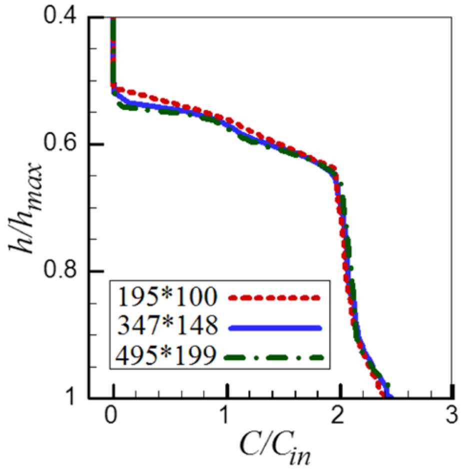

Fig. 2. Mesh sensitivity analysis at r=6 m.

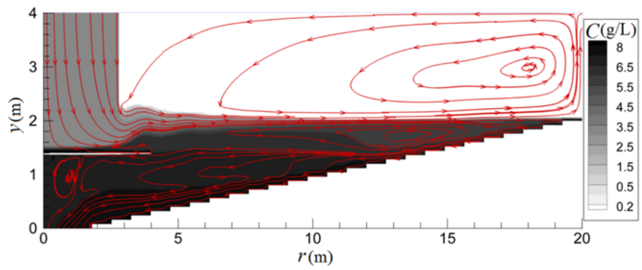

Fig. 3. Concentration contours and flow streamlines.

also checked at other radiuses that are not brought here.

1. Newtonian Model

Results appearing in this section (Figs. 3 through 7) are simulated by using Lakehal et al. [4] settling velocity function, R=0.86, v_{in}= −0.019 m/s, C_{in}=3.2 kg/m^3, C_3=1.0, and β=1.0. Fig. 3 shows that the maximum concentration is at the sludge outlet. Two vortexes are formed in the clear water region. A complex flow field with several recirculation zones appears in the activated sludge region.

Fig. 4 shows the concentration profiles computed at several radial locations which compared with Lakehal et al. [4] results. Fig. 4(a) shows the concentration at r=3 and 6 m, while Fig. 4(b) shows at r=9, 15, and 18 m. The sludge concentration at the bottom of clarifier decreases by getting the distance from the center. Predicted concentration profiles have good agreement with Lakehal et al. especially at radius 3, 6 and 9 m. Small differences can only be seen in radius 15 m and 18 m, that the present simulation gives more concentration than Lakehal et al. Unfortunately, Lakehal et al. do not determine the radius of horizontal baffle. Scaling of Lakehal et al. results show that this radius should be about 3.4 m, but there is no effect of this baffle in the results of Lakehal et al. at r=3 m. Therefore, a small difference may exist between the clarifier geometry used in this article and Lakehal et al. Stepwise geometry used in this simulation might be another source of differences with Lakehal et al.

Fig. 5 shows the vertical profiles of the normalized horizontal velocity computed at several radial locations. A reverse flow would be expected at the bottom of clarifier as it is well predicted in the presented simulation. The agreement between predicted velocity and

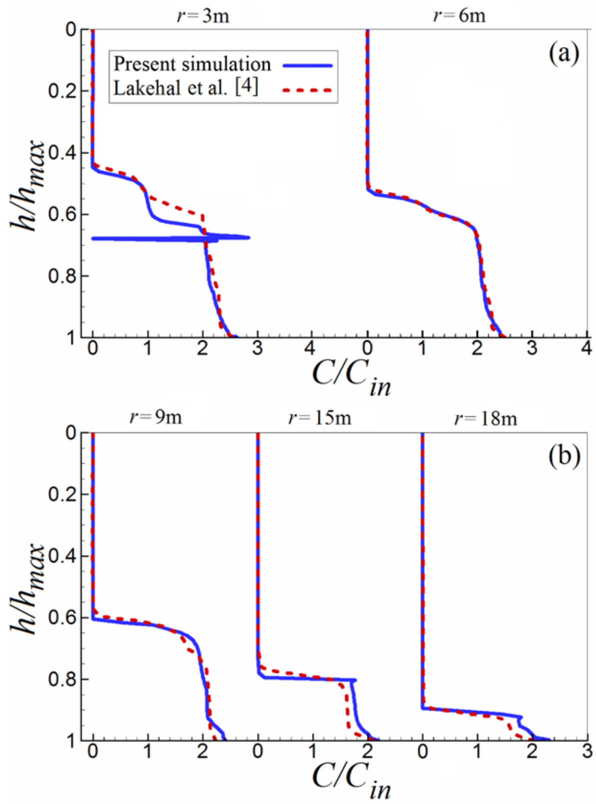

Fig. 4. Concentration profile compared with Lakehal et al. [4]. (a) r=3 and 6 m, (b) r=9, 15 and 18 m.

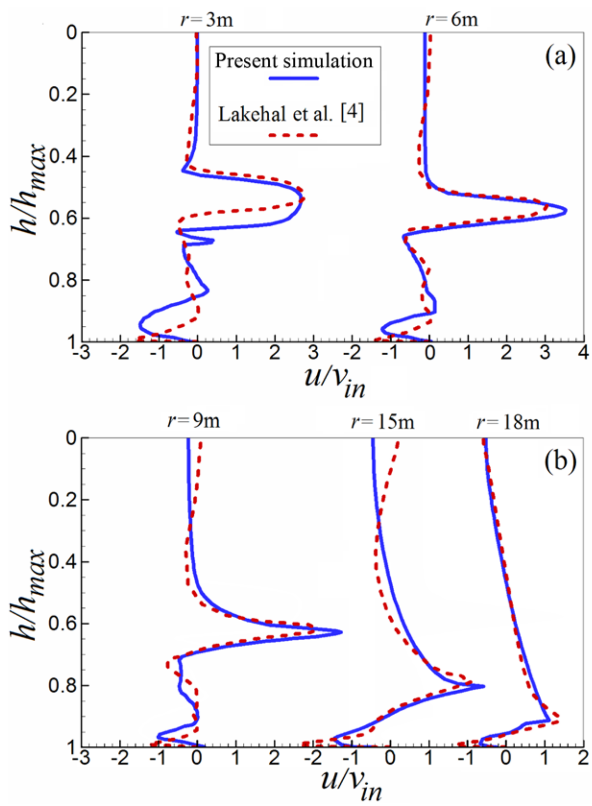

Fig. 5. Velocity profile compared with Lakehal et al. [4]. (a) r=3 and 6 m, (b) r=9, 15 and 18 m.

Table 2. The constants used in settling velocity function (Eq. (11))

Settling velocity function	V_0	r_p	r_h	C_{min}	$V_{s,max}$	Ref.
1	0.005	5.0	0.7	0.01	0.002	Lakehal et al. [4]
2	0.0019	5.0	0.382	0.01	-	Lakehal et al. [4]
3	0.0012	2.501	0.2501	0.0052	-	Weiss et al. [6]
4	0.00549	0.576	2.86	0.0046	-	DeClerck [1]
5	0.00571	3.89	0.273	0.014	-	DeClerck [1]

Lakehal et al. [4] is good. But, there is an exception for the velocity profile at r=3 m compared with Lakehal et al., i.e., the effect of the horizontal baffle on the velocity profile is not observed.

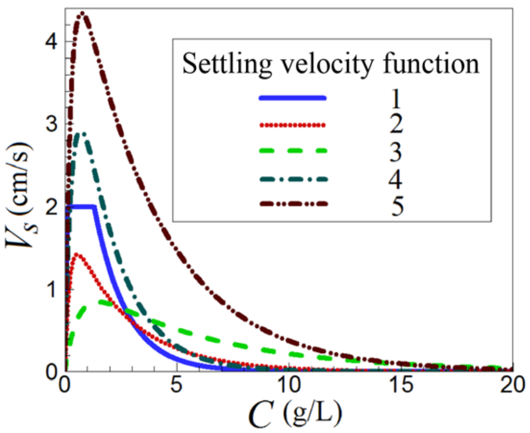

Fig. 6. Variation of settling velocity functions with concentration.

2. Effect of Settling Velocity Function

To evaluate the effect of settling velocity function (SVF), four other velocity functions are used. These functions are based on the Takacs formulation presented in Eq. (11), and are introduced by Lakehal et al. [4], Weiss et al. [6], and DeClercq [1]. Parameters employed in these SVF are introduced in Table 2.

Variation of these velocity functions with concentration is shown in Fig. 6. The 5^{th} SVF gives more settling velocity at all concentrations. The 3^{rd} function gives less settling velocity for concentrations less than 3 g/L.

Figs. 7 and 8 show the difference of concentration and velocity profiles by using various settling velocity functions. Changing the settling velocity function affects the velocity and concentration profiles. Decreasing and increasing the settling velocity compared to 1^{st} SVF leads to decreasing the blanket height. The 5^{th} settling velocity function gives a more reverse flow profile. The 5^{th} function has a bigger settling velocity that creates more momentum for the sludge

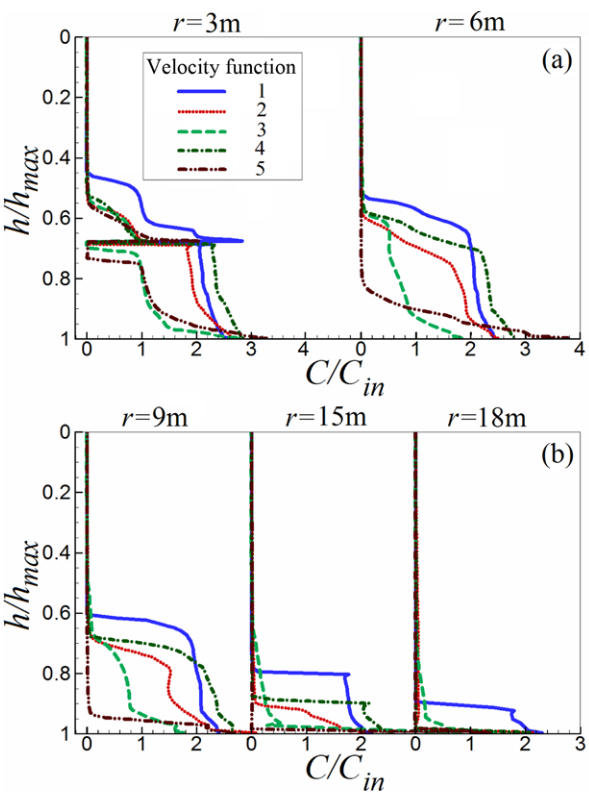

Fig. 7. Comparison of settling velocity functions: Concentration profiles. (a) r=3 and 6 m, (b) r=9, 15 and 18 m.

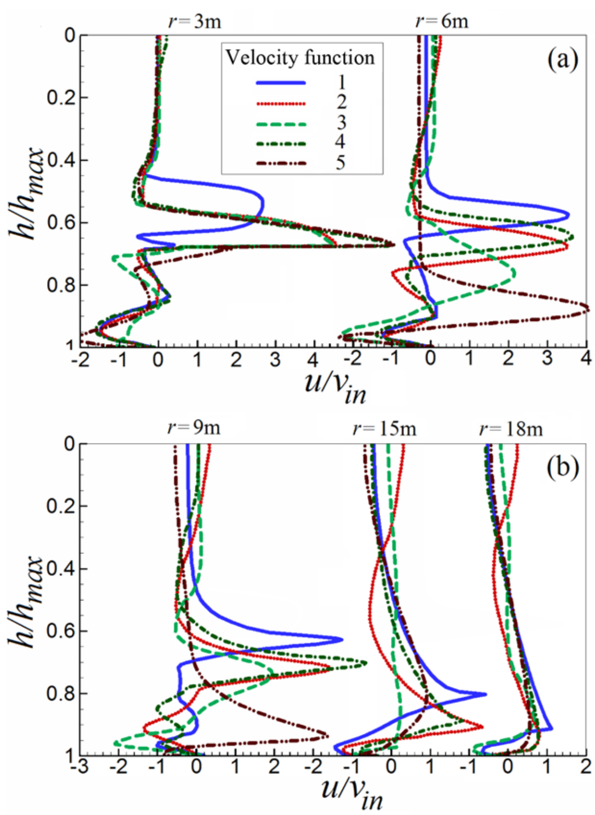

Fig. 8. Comparison of settling velocity functions: Velocity profiles. (a) r=3 and 6 m, (b) r=9, 15 and 18 m.

to move along the inclined surface at the bottom of clarifier. This is an ideal flow field in the secondary clarifier, so adding a substance to increasing settling velocity over the clarifier concentration range may be a good idea for increasing the clarifier performance. The height of sludge blanket is also low in all positions.

3. Non-Newtonian Models

Three types of non-Newtonian fluid models are used for simulation of the flow with activated sludge: Bingham model, Herschel-Bulkley model (including standard and modified) and Casson pseudo plastic model. These models are investigated numerically with various settling velocity functions.

To compare the behavior of these non-Newtonian models, the shear stress is plotted against shear rate at various concentrations (Fig. 9). The Bingham model gives more shear stress at low and high concentration, but gives less in medium concentration. The Herschel-Bulkley model gives more shear stress at low (not very low)

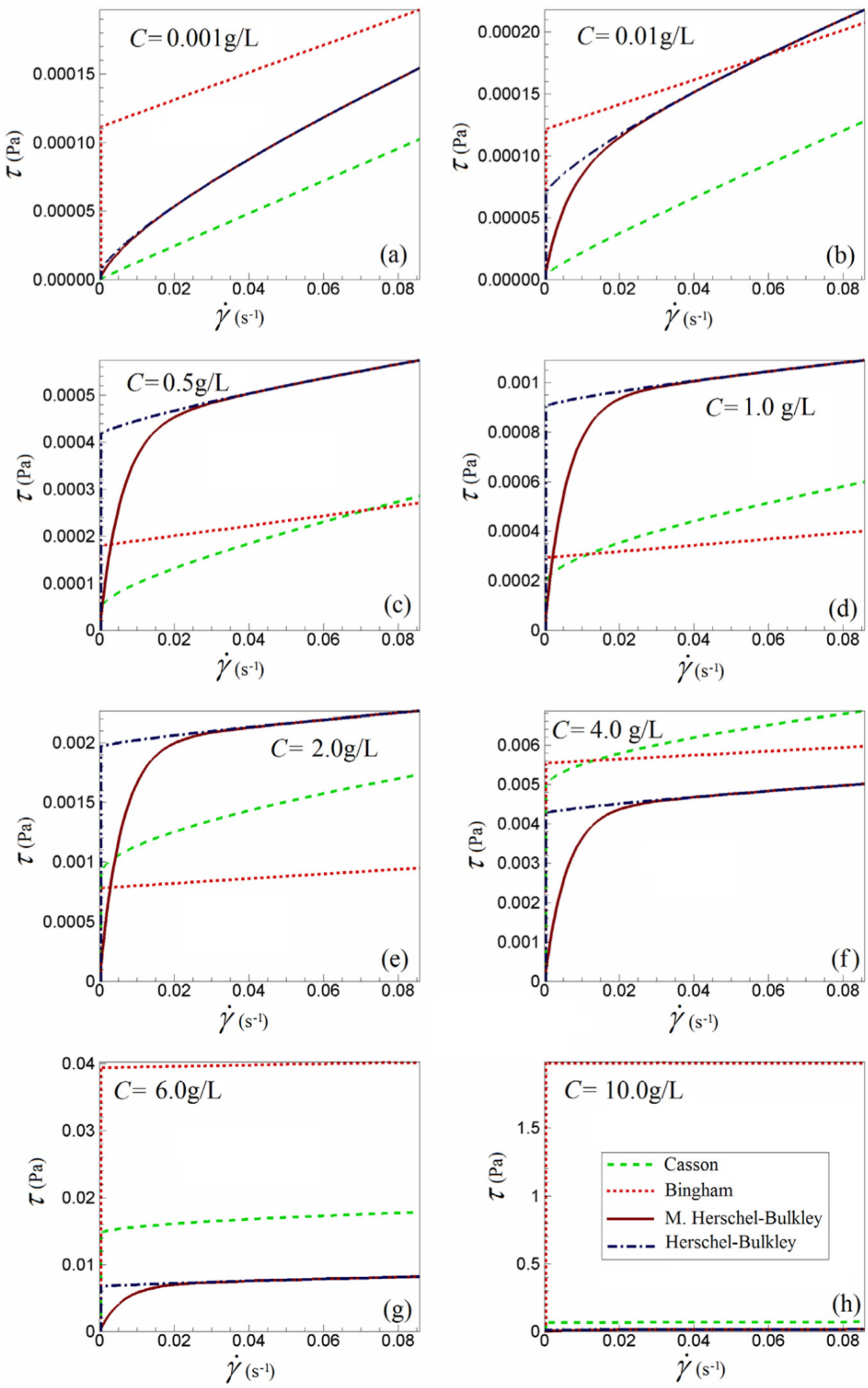

Fig. 9. Shear stress-shear rate charts of non-Newtonian models at different concentrations. (a) C=0.001 g/L, (b) C=0.01 g/L, (c) C=0.5 g/L, (d) C=1.0 g/L, (e) C=2.0 g/L, (f) C=4.0 g/L, (g) C=6.0 g/L, (h) C=10.0 g/L.

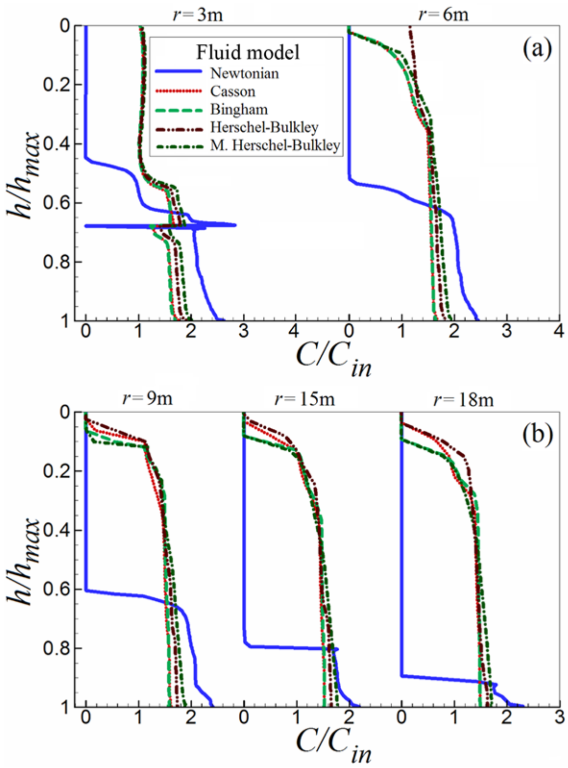

Fig. 10. Comparison of Newtonian and non-Newtonian models using 1st velocity function: Concentration profiles. (a) r=3 and 6 m, (b) r=9, 15 and 18 m.

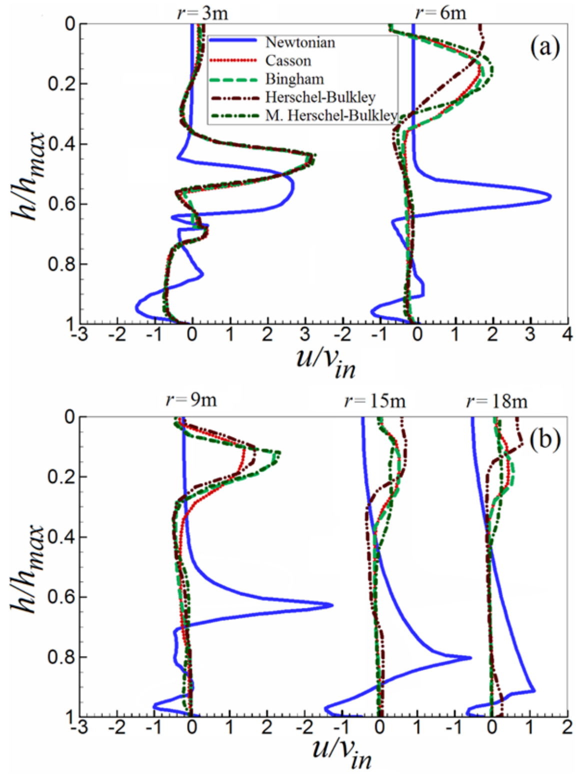

Fig. 11. Comparison of Newtonian and non-Newtonian models using 1st velocity function: Velocity profiles. (a) r=3 and 6 m, (b) r=9, 15 and 18 m.

concentration and gives less concentration at high concentration. The behavior of the Casson model with concentration is against the Bingham model. The difference between the modified and standard Herschel-Bulkley is demonstrated in this figure. The modified Herschel-Bulkley model has no yield stress and is similar to the pseudoplastic model. This is due to the exponential term added to the yield stress. Also, the Casson model only behaves as a pseudoplastic model at low concentration, and at medium and high concentration has a similar pattern like the Herschel-Bulkley model.

3-1. The Effect of Settling Velocity Function

The settling velocity has a tremendous effect on concentration and velocity distribution. Five different settling velocities, which were introduced in section 2, are used. The corresponding concentration and velocity profiles are illustrated in Figs. 10 through 19.

Using 1st settling velocity function, all non-Newtonian models estimate the height of sediment blanket near to the surface of the clarifier. Results are shown in Fig. 10. Sludge blanket height of this velocity function is greater than other velocity function in the Newtonian model. Using non-Newtonian models, including molecular viscosity in concentration equation leads to the overestimation of blanket height. This overestimation prediction also was observed by DeClerck [1]. Velocity profiles are compared with Newtonian and various non-Newtonian models, and presented in Fig. 11. All non-Newtonian models have similar velocity profiles. The non-dimensional height of clear water outlet is h/h_{max}=0.1, so the settled sludge is not removed properly and clear water including a relatively large amount of activated sludge is exiting without any purification. Therefore, this settling velocity function is not acceptable.

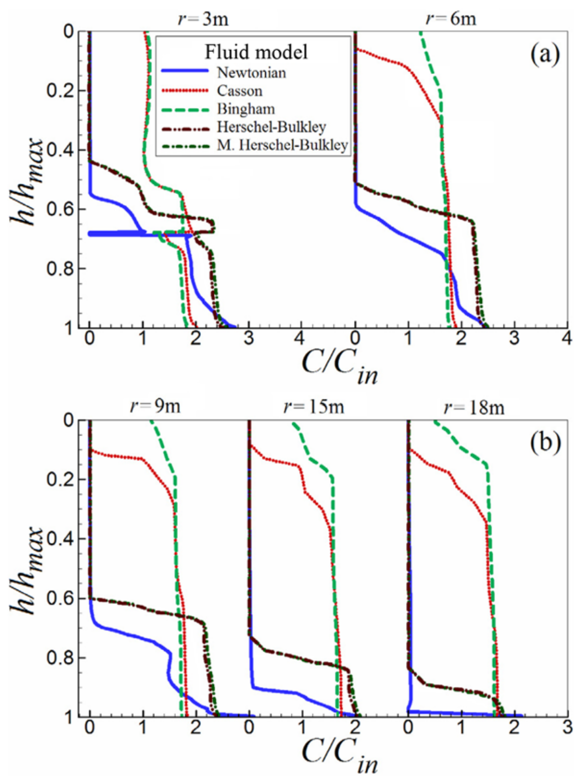

Fig. 12. Comparison of Newtonian and non-Newtonian models using 2nd velocity function: Concentration profiles. (a) r=3 and 6 m, (b) r=9, 15 and 18 m.

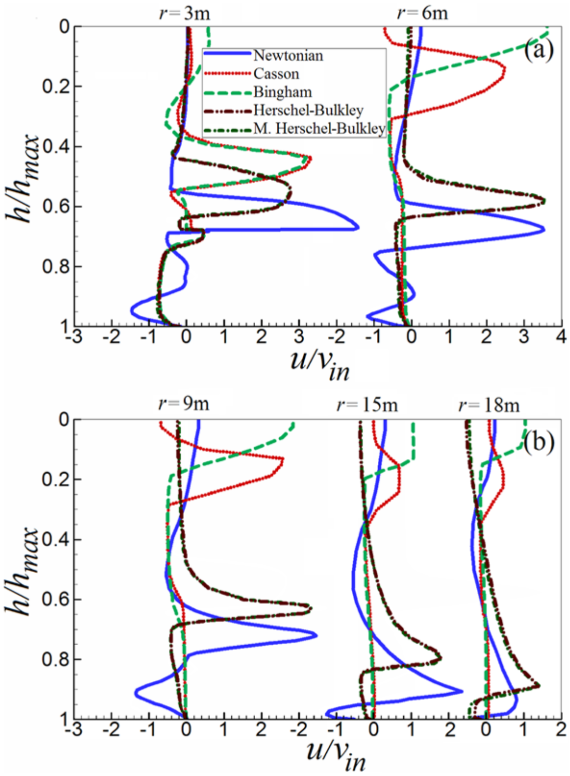

Fig. 13. Comparison of Newtonian and non-Newtonian models using 2^nd velocity function: Velocity profiles. (a) r=3 and 6 m, (b) r=9, 15 and 18 m.

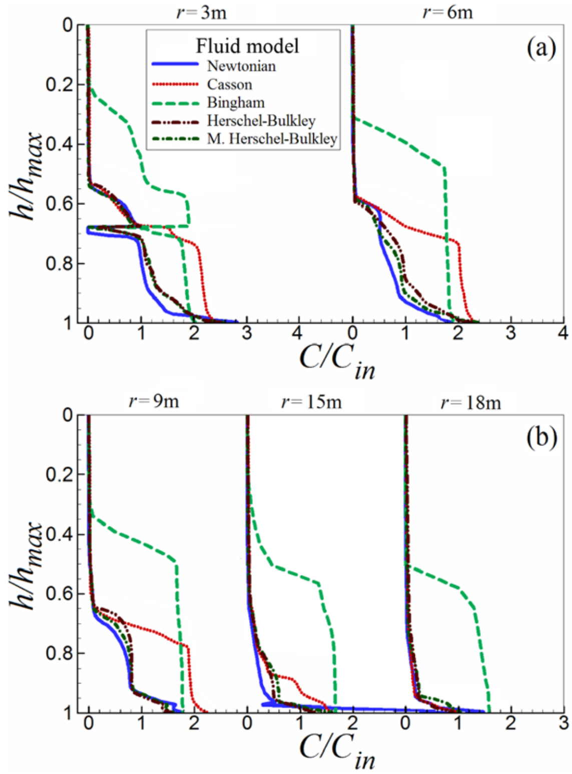

Fig. 14. Comparison of Newtonian and non-Newtonian models using 3^rd velocity function: Concentration profiles. (a) r=3 and 6 m, (b) r=9, 15 and 18 m.

The effect of 2^nd settling velocity function on concentration and velocity profile is examined and presented in Figs. 12 and 13. Casson and Bingham models estimate the blanket height to the clarifier surface. But Herschel-Bulkley and modified Herschel-Bulkley models do not overestimate the blanket height. This overestimation is caused by higher shear stress at high concentration in the Casson and Bingham models. DeClerck [1] indicated that the cause of blanket height overestimation is the yield stress. Comparisons of standard and modified Herschel-Bulkley models show that the effects of yield stress do not play an important role for overestimation of blanket height in this case. Velocity profiles presented in Fig. 13 show close results in the modified and standard Herschel-Bulkley models. Comparison of Casson and Bingham models of Fig. 13 shows that the activated sludge is contained in the outlet of clear water. Therefore, these two models and incorporating 2^nd velocity function cannot be accepted.

Using the 3^rd settling velocity function, no fluid model overestimates the blanket height. Results are presented in Figs. 14 and 15. However, the Bingham model overestimates the activated sludge in comparison to the other models. All models purify the mixture correctly and can be acceptable.

The effects of using the 4^th settling velocity function on concentration and velocity profiles are shown in Figs. 16 and 17. Casson and Bingham models estimate the blanket height at the surface of clarifier, but the Herschel-Bulkley and modified Herschel-Bulkley models do not overestimate the blanket height. Casson and Bingham models show that activated sludge is contained in the outlet of clear water which cannot be acceptable based on the experience

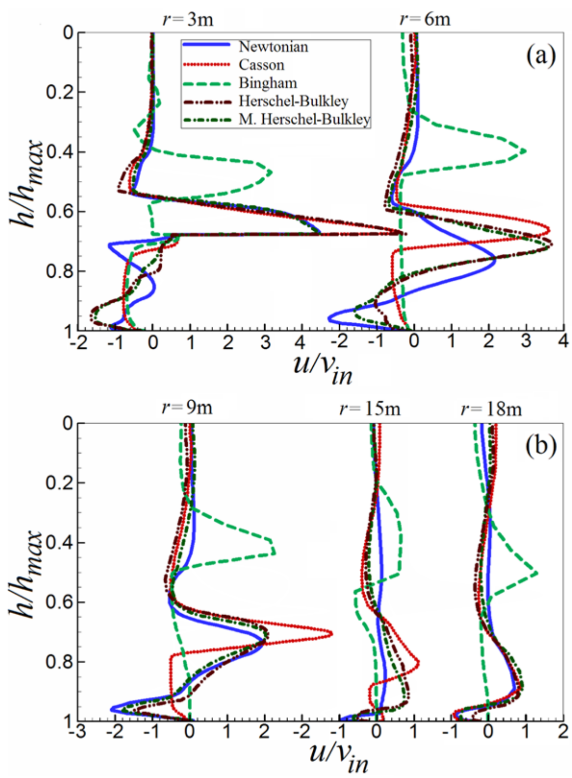

Fig. 15. Comparison of Newtonian and non-Newtonian models using 3^rd velocity function: Velocity profiles. (a) r=3 and 6 m, (b) r=9, 15 and 18 m.

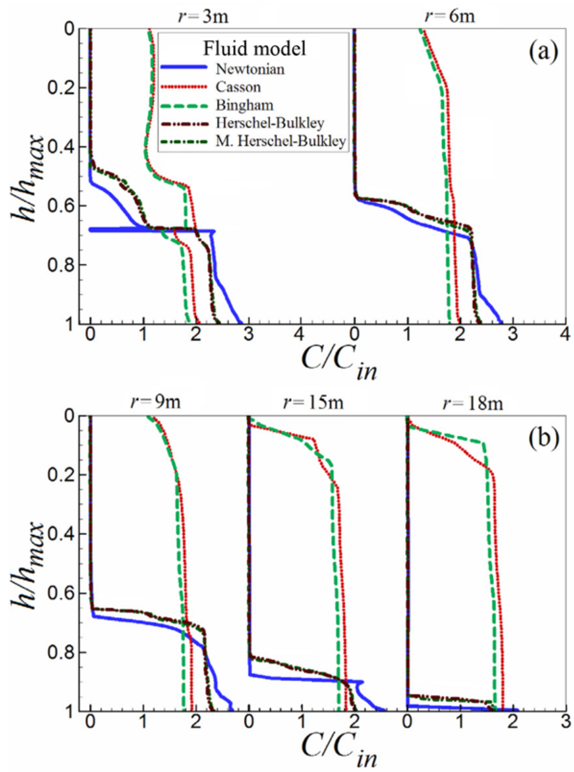

Fig. 16. Comparison of Newtonian and non-Newtonian models using 4th velocity function: Concentration profiles. (a) r=3 and 6 m, (b) r=9, 15 and 18 m.

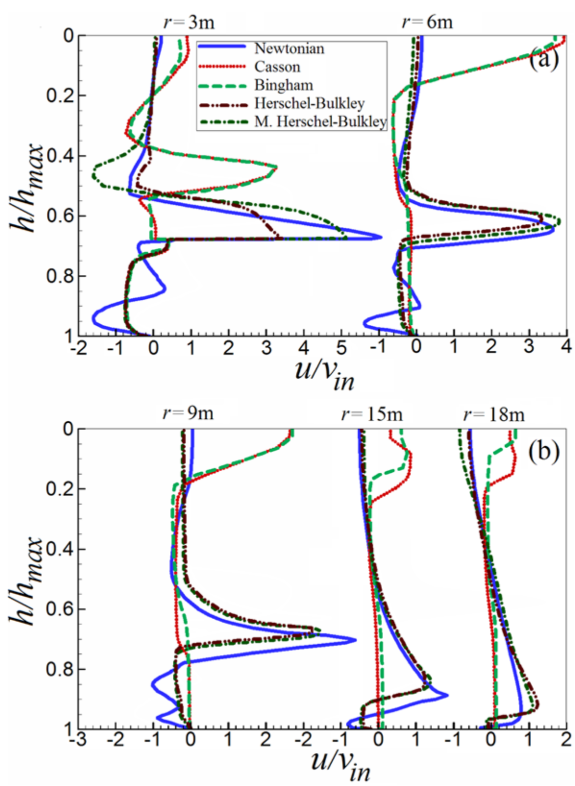

Fig. 17. Comparison of Newtonian and non-Newtonian models using 4th velocity function: Velocity profiles. (a) r=3 and 6 m, (b) r=9, 15 and 18 m.

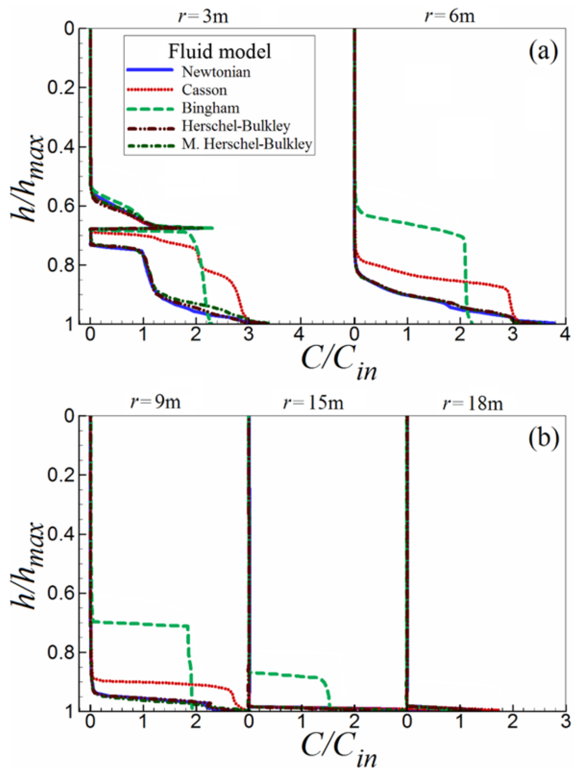

Fig. 18. Comparison of Newtonian and non-Newtonian models using 5th velocity function: Concentration profiles. (a) r=3 and 6 m, (b) r=9, 15 and 18 m.

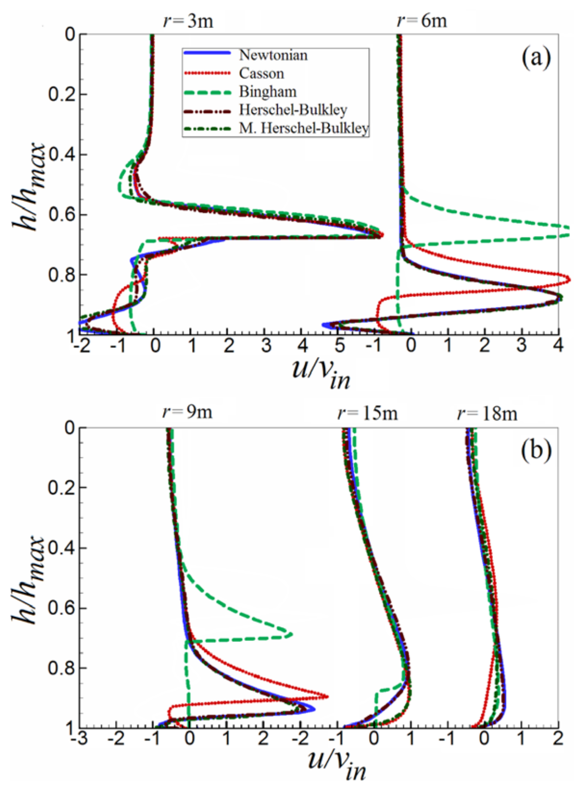

Fig. 19. Comparison of Newtonian and non-Newtonian models using 5th velocity function: Velocity profiles. (a) r=3 and 6 m, (b) r=9, 15 and 18 m.

with this clarifier.

The 5th settling velocity function is based on DeClerck [1] experiment when zeolite is to activated sludge. The density of dry particles is assumed to be 1,450 kg/m^3. The corresponding concentration and velocity profiles are presented in Figs. 18, and 19. All models demonstrate the concentration of the mixture correctly and can be acceptable.

3-2. Selecting the Best Models

A question arises. Which velocity function and non-Newtonian models give better results? Without experimental data the answer is very difficult. The present simulation is compared with Lakehal's [4] numerical results and the authors have not found any published experimental results. This clarifier is now under operation and therefore it should have a proper performance, and the sludge height should be reasonable. Figs. 6 and 9 demonstrate that the settling velocity function and non-Newtonian fluid model are largely depending on the sludge properties. So only the settling velocity functions and non-Newtonian fluid models that are based on a specific sludge are acceptable. Using the 3rd velocity function together with the Casson model, based on Weiss et al. [6] experiments, and also the 4th velocity function together with the modified Herschel-Bulkley model based on DeClercq [1] experiments seems to be appropriate.

Flow streamline, concentration counters, plastic viscosity counters, and shear rate counters of 3rd velocity function using Casson model are shown in Fig. 20. Streamlines show that the flow field is complex with several recirculation zones. Fig. 20(b) shows that how viscosity of activated sludge is defined. Plastic viscosity is proportional to shear rate inversely. So at low shear rate, the value of plastic viscosity is high. Comparing Figs. 20(b) and 20(c), completely similar zone can be found in the clarifier. At the clear water zone above the activated sludge, low shear rate also tends to increase viscosity. Plastic viscosity is proportional to the concentration, so this correlation corrects plastic viscosity in the clear water zone. Overestimation of some non-Newtonian models with some velocity function is due to the lack of proper modification of plastic viscosity by considering concentration. Concentration does not decrease the viscosity at upper zone sufficiently and consequently overestimated activated sludge is observed. Similar trend can be found by using of 4th velocity function and modified Herschel-Bulkley model that are not brought here.

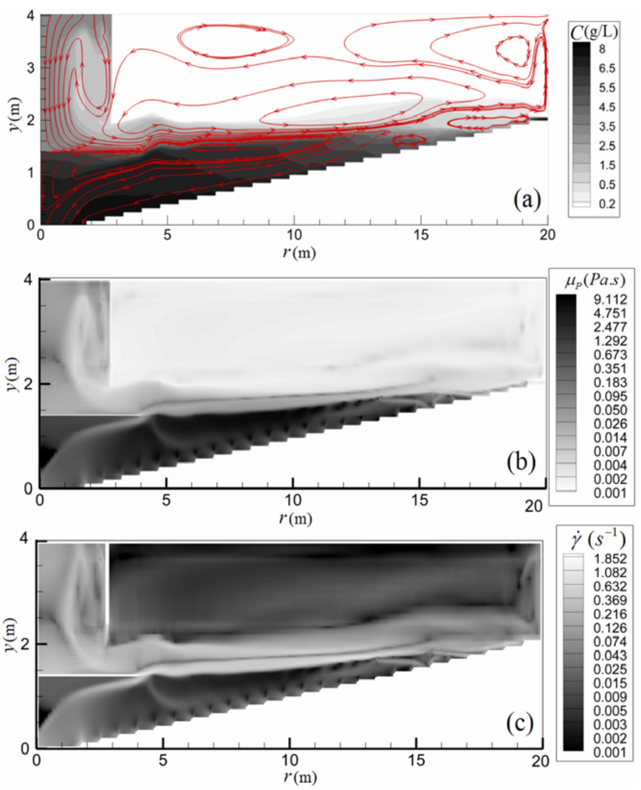

Fig. 20. (a) Concentration counters and flow streamlines, (b) Plastic viscosity, and (c) Shear rate: 3rd settling velocity function, and Casson model.

CONCLUSION

The flow field is solved by using the Newtonian model and the results are compared with another numerical simulation provided by Lakehal et al. [4]. Concentration and velocity profiles show that numerical simulation has good agreement with Lakehal et al.

Five settling velocity functions are used. It is shown that the flow field and sludge blanket height largely depends on the settling velocity function. Low sludge blanket height can be expected at low settling velocity due to decreasing particle settling capacity. Also, low sludge blanket height can be expected at high settling velocity due to high reverse flow below the horizontal baffle and more compressed settled sludge.

Four types of non-Newtonian fluid--Bingham plastic, Casson pseudo plastic, Herschel-Bulkley and modified Herschel-Bulkley models--are used. Comparison of non-Newtonian results in five settling velocity functions shows that:

1. 3rd settling velocity function predicts very low settling velocity and still does not overestimate the blanket height.
2. 5th settling velocity function predicts very high settling velocity and still does not overestimate the blanket height.
3. 2nd settling velocity function predicts low settling velocity only Casson and Bingham models overestimate the blanket height.
4. 4th settling velocity function predicts high settling velocity only Casson and Bingham models overestimate the blanket height.
5. 1st settling velocity function predicts medium settling velocity and all models overestimate the blanket height.

Results show that overestimation of blanket height does not relate to yield stress in the used clarifier with specific geometry and loading. Modified and standard Herschel-Bulkley models give close results to each other. It is concluded that the Bingham models give high shear stress at high concentration. Therefore, more overestimation potential of this model is due to the high plastic viscosity induced at high concentration.

The behavior of activated sludge is depends on the property of sludge. The effect of flocculation is considered in settling velocity. Therefore, only the corresponding settling velocity function and non-Newtonian fluid model based on a specific sludge and experiment are acceptable. It is concluded that only two model gives reasonable results in present clarifier:

- Casson model together with 3rd settling velocity function.
- Modified Herschel-Bulkley model together with 4th settling velocity function.

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