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Dedicated to Professor Liviu Literat, at his 80th anniversary

SEDIMENTATION SIMULATION OF COAGULATED YEAST SUSPENSIONS FROM WASTEWATER

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ABSTRACT. On the basis of mathematical modelling and numerical simulation the batch settling of coagulated yeast suspensions was analysed. Time and space behaviour of the solids height and critical height of sediment in gravitational settling, has shown similar results comparative to experimental data. The method offers the possibility to predict by simulation the settling rate for the consolidation region, a key settling variable difficult to be measured experimentally but important for the settler design.

Keywords: *sedimentation, settling rate, coagulated yeast suspensions, simulation*

INTRODUCTION

Solving the water pollution problem by colloidal and micro suspended particles resulting from breweries has been a challenge for a long time. As it is known for colloids and fine particles, main transport mechanisms include convection, Brownian diffusion, shear-induced diffusion, inertial lift, gravitational settling and lateral migration. Their relative importance strongly depends on the shear rate, particle size and bulk concentration. To improve the solid-liquid separation of micro-particles in aqueous suspensions before sedimentation and/or before filtration a common used method is aggregation (coagulation or flocculation). Some studies concerning settling of yeast micro-particles have shown that coagulation or flocculation, as a pre-treatment step before conventional sedimentation, could improve colloidal and micro-particles removal from aqueous suspension [1, 2].

Investigations of yeast particles sedimentation in water demonstrated that lack or low and limited separation may occur if no coagulant was added to induce a destabilization between yeast particles [3]. Pre-treatment by coagulation

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or flocculation using chemical additives destabilizes colloidal suspensions, allowing colloidal and fine particles to agglomerate into micro- and large flocks which settle more quickly than single particles because of their larger mass to surface area ratio.

The sedimentation behaviour of aggregated suspensions strongly depends on concentration. Experimental sedimentation in a batch system shows different regions of sedimentation, as presented in Figure 1.

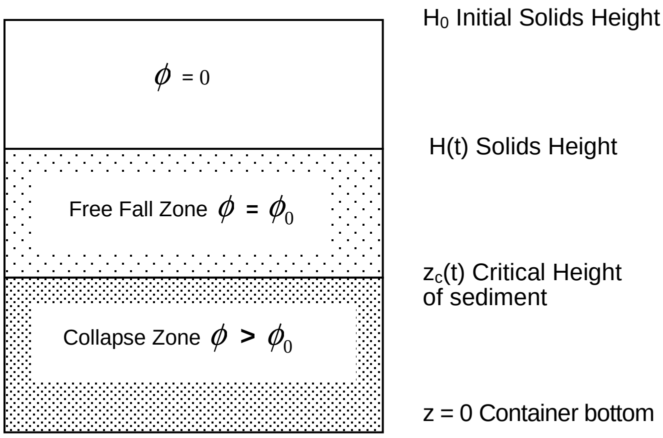

Figure 1. Schematic illustration of sedimentation zones.

In dilute suspensions ($\Phi = \Phi_0$) or at low degrees of aggregation, particles and aggregates settle independently and their motion is unaffected by the motion of other particles (free sedimentation). In more concentrated suspensions ($\Phi > \Phi_0$) or higher degrees of aggregation, sedimentation is influenced by hydrodynamic interaction with other moving particles and *hindered settling* or *zone settling* is observed [4-6]. The transition from free sedimentation to hindered settling occurs at a concentration which depends on the degree of aggregation. Zone settling may be found at quite low solids concentrations if the particles are aggregated to a large extent. For high concentrations of aggregated particles compression becomes significant and this is typically observed at the bottom of the sedimentation vessel.

Mathematical models of the sedimentation process are needed in industrial applications for the description, simulation, design and control of solid-liquid separation processes of suspensions, as it is also the case of coagulated yeast suspensions from wastewater.

According to Buscall and White [7], the system of equations (1) – (4) describing the sedimentation process consists in:

$$\frac{\partial \phi}{\partial t} = \frac{\partial (\phi u)}{\partial z} \tag{1}$$

$$u = \frac{u_{st}(1-\phi)}{r(\phi)}\left[1 + \frac{1}{\Delta\rho \cdot g \cdot \phi} \cdot \frac{\partial p}{\partial z}\right] \tag{2}$$

where:

$$\frac{\partial u}{\partial z} = 0 \quad \text{for} \quad p < P_y(\phi) \tag{3}$$

$$\frac{\partial u}{\partial z} = \frac{k(\phi)}{\phi}[p - P_y(\phi)] \quad \text{for} \quad p \geq P_y(\phi) \tag{4}$$

Considering that suspension is fully networked, the numerical modelling technique solves the system of equations and computes the time evolution of the two moving boundaries which describe the settling and the consolidation process [8].

For the simulation the mathematical model described below has been implemented in MatLab software. Dimensionless sedimentation equations are obtained by the use of the following scaling:

$$Z = \frac{z}{H_0} \qquad Z_c(T) = \frac{z_c(t)}{H_0} \qquad L(T) = \frac{H(t)}{H_0} \tag{5}$$

$$T = \frac{t \cdot u_{st} \cdot (1-\phi)}{r(\phi) \cdot H_0} \tag{6}$$

$$\Phi(Z,T) = \frac{\phi(z,t)}{\phi_0} \tag{7}$$

$$U(Z,T) = \frac{u(z,t) \cdot r(\phi_0)}{u_{st} \cdot (1-\phi_0)} \tag{8}$$

$$\Pi(Z,T) = \frac{P(z,t)}{P_y(\phi_0)} \qquad f(\Phi) = \frac{P_y(\phi)}{P_y(\phi_0)} \tag{9}$$

$$B(\Phi) = \frac{(1-\phi_0 \cdot \Phi) \cdot r(\phi_0)}{(1-\phi_0) \cdot r(\phi_0 \cdot \Phi)} \tag{10}$$

For the consolidation zone to exist:

$$\varepsilon = \frac{P_y(\phi_0)}{\Delta\rho \cdot g \cdot \phi_0 \cdot H_0} < 1 \tag{11}$$

The solution in the free-fall zone ($Z_c(T) \le Z \le L(T)$) may be obtained from the set of equations:

$$\Phi(Z,T) = 1 \quad (12)$$

$$U(Z,T) = -\frac{dL}{dT} \quad (13)$$

$$\Pi(Z,T) = \frac{1}{\varepsilon}\left[1 + \frac{dL}{dT}\right]\left[L(T) - Z\right] \quad (14)$$

In the collapse zone ($0 < Z < Z_c(T)$) the dimensionless equations and boundary conditions are:

$$\frac{\partial \Phi}{\partial T} = \frac{\partial}{\partial Z}(\Phi \cdot U) \quad (15)$$

$$U(Z,T) = B(\Phi) \cdot \left[1 + \frac{\varepsilon}{\Phi} \cdot f'(\Phi)\frac{\partial \Phi}{\partial Z}\right] \quad (16)$$

$$\Phi(Z,0) = 1 \quad (17)$$

$$U(0,T) = 0 \quad (18)$$

$$\Phi(Z_c(T),T) = 1 \quad (19)$$

$$U(Z_c(T),T) = -\frac{dL}{dT} \quad (20)$$

The equation connecting the solids height to the critical height is:

$$\left[1 + \frac{dL}{dT}\right] \cdot \left[L(T) - Z_c(T)\right] = \varepsilon \quad (21)$$

The functions B(Φ) and f(Φ) may be detailed by:

$$B(\Phi) = \left[\frac{1 - \phi_0 \cdot \Phi}{1 - \phi_0}\right]^{5.5} \quad (22)$$

$$f(\Phi) = \frac{C^n \cdot \Phi^n - 1}{C^n - 1} \quad (23)$$

The parameter *C* is and defined by:

$$C = \frac{\phi_0}{\phi_g} \quad (24)$$

where the parameter ϕ_g represents the lowest volume fraction for which the flocculated particles are networked. The parameter *n* represents the index in yield stress function.

When equations are rewritten in terms of Φ and dimensionless solids flux Q=Φ U, they describe the collapse zone by:

$$\frac{\partial Q}{\partial Z} = \frac{\partial \Phi}{\partial T} \tag{25}$$

$$\frac{\partial \Phi}{\partial Z} = \frac{1}{\varepsilon \cdot f'(\Phi) \cdot B(\Phi)} \left[Q - \Phi \cdot B(\Phi) \right] \tag{26}$$

$$\Phi(Z,0) = 1 \tag{27}$$

$$Q(0,T) = 0 \tag{28}$$

$$\Phi(Z_c(T),T) = 1 \tag{29}$$

$$Q(Z_c(T),T) = -\frac{dL}{dT} \tag{30}$$

$$\left[1 + \frac{dL}{dT} \right] \cdot \left[L(T) - Z_c(T) \right] = \varepsilon \tag{31}$$

Equations (25) – (31) must be solved numerically to obtain the volume fraction $\Phi(Z,T)$, the solids height L(T), the solid flux Q(Z,T) and the critical height Z_c(T).

The significance of the symbols is: $B(\Phi)$ - scaled hydrodynamic drag function, C - constant in $f(\Phi)$, dp_{50} - mean particles diameter, $f(\Phi)$ - scaled yield stress function, g - gravitational constant, $k(\phi)$ - dynamic compressibility of the flocculated network, L(T) - scaled solids height, n - index in yield stress function, p – network pressure, $P_y(\phi)$ - yield stress of a flocculated suspension, Q - scaled solids flux, $r(\phi)$ - hydrodynamic interaction factor, t - time, T - scaled time, u - solids velocity vector, u_{st} - Stokes settling velocity of an isolated particle, U(Z,T) -scaled solids speed, w - fluid velocity vector, z - vertical spatial coordinate, z_c(t) - critical height, boundary of the consolidation zone, Z - scaled vertical spatial coordinate, Z_c(T) - scaled critical height, $\Delta\rho$ - difference between solid and fluid densities, ε - dimensionless number characterizing the flocculated suspension, η_l - fluid viscosity, ρ_s - density of the solids, ρ_l - liquid density, ϕ - volume fraction of suspension occupied by solids, ϕ_g - gel point of a flocculated suspension, ϕ_0 - initial volume fraction, $\Phi(Z,T)$ - scaled solids volume fraction, $\Pi(Z,T)$ - scaled network pressure.

Numerical values for the parameters taken into consideration in the model are:

- initial solids height H_0 = 102 mm
- fluid viscosity η = 10^{-3} Pa*s
- solid density ρ = 1100 kg/m^3
- sedimentation rate u_{St} = 2.725*10^{-4} m/s (determined for particles diameter d_p =50 μm)
- initial volume fraction $\phi_0 = 0.014$

The goal of the paper has been the implementation of the sedimentation model equations for the case of yeast suspensions from a brewery and comparison of the simulation results with experimental data in order to validate the model for further use of the simulator in equipment design and operation optimization of the sedimentation process.

RESULTS AND DISCUSSION

First, on the basis of the model described above, a simulator has been built in MatLab software environment. The simulator describes the sedimentation of suspensions in the free fall and consolidation zones. Second, the parameters of the simulator have been fitted to the particular case under study. Furthermore, the parameters *n* and *C* of the model have been chosen on the basis of the experimental results.

In order to find out the suitable value of the model parameter n for the investigated sedimentation process of coagulated yeast suspensions, different simulations have been performed, for different values of *n*. Analysing the simulation results it has been decided the most suitable value for *n* to be 5.

Consequently, the simulation of the sedimentation process was performed with the parameters *C* = 3 and *n* = 5. Figure 2 presents the computed scaled volume fraction Φ as a function of Z, in the consolidating zone and at various scaled time moments T.

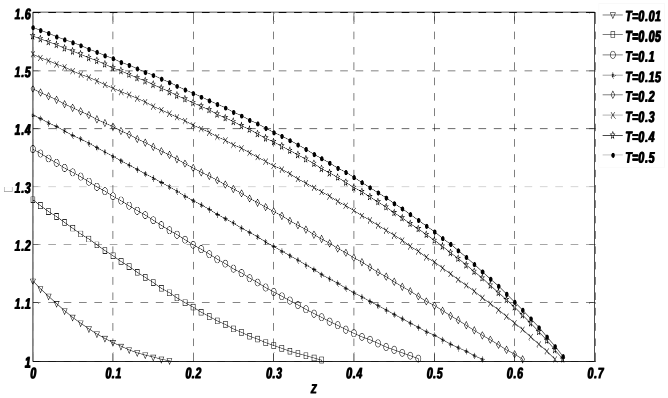

Figure 2. Volume fraction profiles for *n* = 5, *C* = 3, ε = 0.1, at different time moments.

Figure 3 shows the simulated solids height H(t) and the critical height of sediment $z_c(t)$ as a function of time.

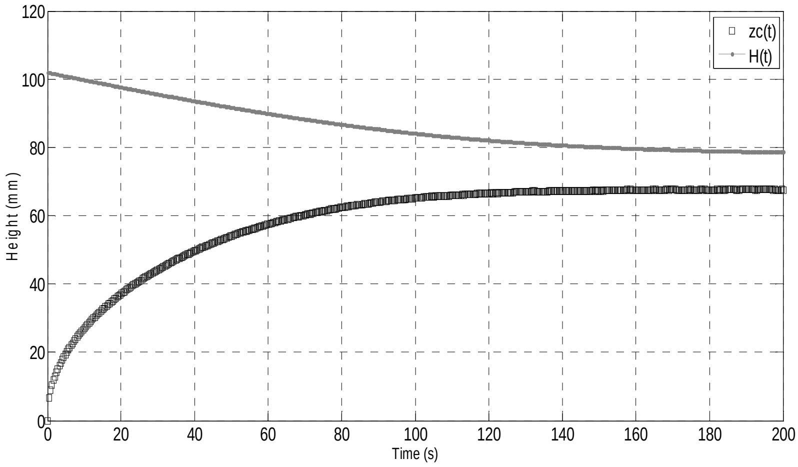

Figure 3. Critical height of sediment $z_c(T)$ and solids height H(t) for n =5, *C* =3, ε =0.1.

The experimental results show that at the initial time, t = 0, H(t) = H_0 = 102 mm and when all the large particles are settled H(t) = H_{final} = 78.588 mm.

Figure 4 shows the progress of the experimental solids height as a function of time, compared to the results obtained by the numerical simulation.

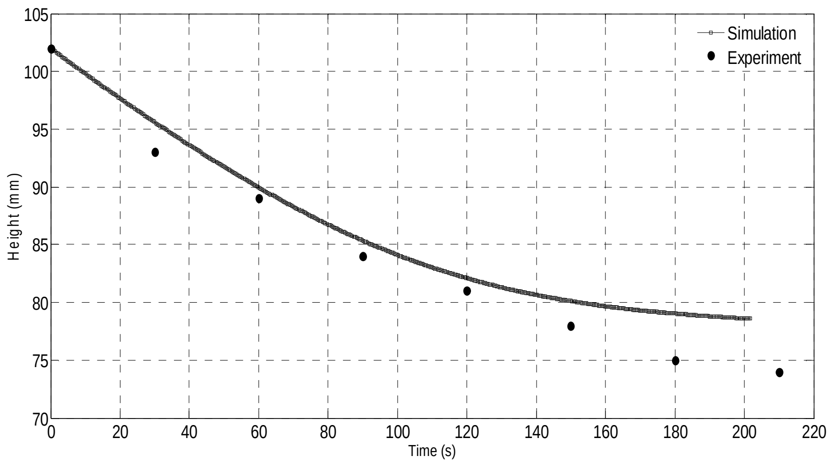

Figure 4. Comparison of solids height change in time for both experimental and simulated case.

Comparing the experimental and the modelling results it may be concluded that a good match between the simulation and the experiment was obtained. Comparison between the experimental sedimentation time and the simulated sedimentation time has been also performed and the results show values close one to each other: t_{exp} = 210 s and t_{sim} = 202 s.

CONCLUSIONS

The aim of this study was to build a sedimentation simulator in MatLab software, in order to investigate the sedimentation of coagulated yeast suspensions from wastewaters. The simulator reveals the complex time and space evolution of the sediment concentration in the settler.

An important outcome of the simulator is its ability to compute the change in time of the critical height, an important process variable which is very difficult to be experimentally observed due to the poorly delimited boundary of the critical sediment height.

The simulator also offers the means for investigating the influence of different settling parameters on the sedimentation process. Such parameters that influence the sedimentation and that can be observed with the simulator are: yeast particle diameter, initial suspension concentration, viscosity, differences between solid and liquid densities and gel point of flocculated suspensions. The simulator is also a useful tool for the computation of the theoretical sedimentation time (time when all the solid particles are settled).

As the simulator presents the complex time and space behaviour of important sedimentation variables, such as: sedimentation rate, solid concentration, time of sedimentation, it may be further used for the design and optimization operation of the settler.

EXPERIMENTAL SECTION

In order to determine the solids and critical heights the experimental measurements of sedimentation were carried out in a batch settling test with 5 graduated cylinders having D = 50 mm and H = 500 mm, by the same method described in the earlier work [1]. Wastewater from brewery “URSUS”, Cluj-Napoca, Romania was used as suspended material for the experimental research. Untreated effluents typically contain suspended solids in the range of 10 – 60 mg/L, biochemical oxygen demand (BOD) in the range of 1,000 – 5,000 mg/L, chemical oxygen demand (COD) in the range of 1,800 – 3,000 mg/L, and nitrogen in the range of 30 – 100 mg/L. In the experimental sample Ferric chloride ($FeCl_3$) with the concentration 1150 ppm was used as coagulant. Sedimentation curve has been experimentally determined by the measurement of the moving solids height during time.

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