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Dynamic simulation of tailing thickener at the Tabas coal washing plant using the phenomenological model

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ABSTRACT

Real time dynamic simulation provides a powerful tool to control the mineral processing plants with the minimum cost. In this study, the dynamic simulation was carried out for the thickener at coal washing plant. Therefore, the parameters of the phenomenological model for the sedimentation and thickening were determined at different conditions. Dynamic simulation was carried out for each condition and the effect of feed flow rate variations on solid volume fraction of the thickener underflow and bed height was investigated. For all conditions, it was observed that when feed flow rate increases, the solid volume fraction of discharge and bed height increase. It was also observed that, in the case of the flocculated suspension, the maximum solid volume fraction of the thickener underflow decreases and the bed height increases with pH reduction, for two size fractions. Also, the maximum solid volume fraction of the thickener underflow for $d_{80} = 275$ μm is higher than that of $d_{80} = 125$ μm and the height of compression zone for $d_{80} = 125$ μm is higher than that of $d_{80} = 275$ μm at the certain pH and flocculant dosages.

1. Introduction

Over the past few decades, on-line analysis techniques have been developed and applied in the mineral and energy industries for the measurement of mineral processing variables. This has led to increase the throughput and product quality while reducing the processing costs and minimizing emissions (Death et al., 2002). Soft sensor models are being developed for the plant variables that have previously been unavailable (Gonzalez, 1999).

Therefore, advanced control techniques can be used for controlling the mineral processing plants. Real time dynamic simulation provides a powerful tool to control the mineral processing plants with the minimum cost. Many simulation techniques exist for simulation in the mineral processing industry. However, most of the simulation packages are based on steady state condition. Such simulation packages cannot simulate the dynamic behavior and interactions of processing units within a circuit. Such dynamic variations and interactions can cause major problems for process control and optimization. Dynamic simulation is a powerful tool in many industries such as aerospace, military, automotive and steel making. Today, dynamic simulation is used for plant design, optimization and control of the plant. Dynamic simulation is used for the circuit response to changes in feed properties and operating unit. This method is an inexpensive and effective method for the investigation of a circuit or optimization process (Liu and Spencer, 2004).

The settling of flocculated suspensions is a subject that has attracted the attention of many authors but most of these works have empirical nature. Until 1998, some researchers tried to present the models for design of thickener but these models are empirical. Burger and Concha (1998); Burger et al. (1999) and Garrido et al. (2004) proposed the phenomenological model for the sedimentation and thickening process by considering several constitutive assumptions. The phenomenological theory of sedimentation–consolidation processes provides a useful model for the simulation, design and control of the thickeners.

Usher et al. (2009) developed the suspension dewatering equations based on aggregate densification. They presented the liquid flow velocity around and through aggregates.

Gladman et al. (2010) investigated the validation of the presented model by Usher. They validated the model by operating a pilot column continuously and measuring the underflow solids. They confirmed that this model was the most accurate at the shortest residence times and lowest bed heights, but less accurate for longer residence times and higher beds. This was due to the changes in the dewatering properties of flocculated aggregates over time, which had not been adequately considered in the model.

Van Deventer et al. (2011) used the aggregate densification theory to predict the final equilibrium bed height by densification rate and bed compression. Moreover, the relationship between aggregate size and thickening time was obtained.

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Ebrahimzadeh et al. (2013) simulated the semi-industrial pilot plant thickener using the CFD approach. They investigated the effect of different parameters such as feed flow rate, solid percentage of the feed and feed size on the thickener performance.

Gálvez et al. (2014) presented a method for optimizing the design of dewatering systems that employs hydrocyclones and thickeners. Mathematical models were generated to determine the maximum water recovery rate and to determine the minimum cost of the equipment and the corresponding system structure for the given water recovery rates. The models were based on mixed integer nonlinear programming.

Betancourt et al. (2014) investigated dynamic simulation the thickener. In this research, operating charts were calculated to be used for the control of steady states, in particular, to keep the sediment level and the underflow volume fraction at desired values. A numerical scheme and a simple regulator were proposed and numerical simulations were carried out.

It was observed that many works have been done in the field of sedimentation and thickening process but few researches have been done in the field of dynamic simulation of thickener.

The purpose of this research is to simulate of an industrial thickener using phenomenological model. There are several parameters that affect the thickener performance. In this paper, we have investigated the effect of particle size, pH, flocculant dosage and feed flow rate variations on the thickening performance at different times for the tailing thickener of the coal washing plant.

2. Mathematical model of sedimentation and thickening

Burger and Concha (1998); Burger et al. (1999) and Garrido et al. (2004) presented the following field equation for the solid volume fraction (φ) in the thickener as a function of height $0 \le z \le L$ and time $0 \le t \le T$:

$$\frac{\partial \varphi}{\partial t} + \frac{\partial}{\partial z}\left(q(t) \times \varphi + f_{bk}(\varphi)\right) = -\frac{\partial}{\partial z}\left(f_{bk}(\varphi)\frac{\sigma_e^{/}(\varphi)}{\Delta\rho \times g \times \varphi}\frac{\partial \varphi}{\partial z}\right) \tag{1}$$

Where, φ is the solid volume fraction, z is the vertical coordinate (Height), Δρ is the solid–fluid density difference and g is acceleration of gravity. In the equation (1):

$q(t) = (Q_D/S) \le 0.$

Where, Q_D is the volumetric discharge rate and S is the cross-sectional area of the thickener.

In Equation. (1), $f_{bk}(\varphi)$ is the batch flux density function. It is usually assumed that $f_{bk}(\varphi) = 0$ for $\varphi = 0$ and $\varphi = 1$ and $f_{bk}(\varphi) < 0$ for $0 < \varphi < 1$. The method for determination of batch flux density function has been presented in Section 3.2.2.

In Equation. (1):

$$\sigma_e^{/}(\varphi) = \frac{d\,\sigma_e(\varphi)}{d\varphi} \begin{Bmatrix} = 0 & for\ \varphi \le \varphi_c \\ > 0 & for\ \varphi > \varphi_{c.} \end{Bmatrix}$$

Where $\sigma_e(\varphi)$ is the effective solid stress and φ_c is the critical solid volume fraction or gel point. The critical solid volume fraction (φ_c) or gel point is the solid volume fraction at the beginning of the compression zone and is the lowest volume fraction that flocs begin to touch each other. By increasing the pressure, the solid volume fraction increases. The effective solid stress ($\sigma_e(\varphi)$) which represents the stress in the compression zone is the stress which must be exceeded by an applied stress before the consolidation will occur. Buscall and White (1987) suggested that the effective solid stress, $\sigma_e(\varphi)$, is a function of the solid volume fraction, φ, and can be obtained using Equation. (2):

$$\sigma_e(\varphi) = \sigma_0\left((\varphi/\varphi_c)^n - 1\right) \tag{2}$$

Where parameters σ_0 and n are the constant parameters that are obtained using experimental tests. Equation. (1) is a second order quasilinear parabolic partial differential equation degenerating into first order hyperbolic type for the interval of solution values $[0, \varphi_c]$. Equation. (1) does not have an analytical solution, but can be solved numerically using a finite difference method. The following initial conditions for solving degenerate parabolic partial differential equation (PDE) should be determined:

$$\varphi(z, 0) = \varphi_0(z) \qquad 0<z<L \tag{3}$$

$$\varphi(L, t) = \varphi_1(t) \qquad 0<t<T \tag{4}$$

The boundary conditions at $z = 0$ and $z = L$ for solving the degenerate parabolic partial differential equation (PDE) are as follows:

$$f_{bk}(\varphi(0,t))\left(1 + \frac{\sigma_e^{/}(\varphi(0,t))}{\Delta\rho \times g \times \varphi(0,t)}\frac{\partial \varphi(0,t)}{\partial z}\right) = 0 \tag{5}$$

$$\frac{Q_D(t)}{S} \times \varphi(L,t) + (f_{bk}(\varphi(L,t))\left(1 + \frac{\sigma_e^{/}(\varphi(L,t))}{\Delta\rho \times g \times \varphi(L,t)}\frac{\partial \varphi(L,t)}{\partial z}\right) = \frac{Q_F \times \varphi_F}{S} \tag{6}$$

Where, Q_F is the mixture feed flow rate and φ_F is the solid volume fraction of the thickener feed.

2.1. Discretization

As mentioned before, Equation. (1) is complicated and does not have an analytical solution, but can be solved numerically using the finite difference method (PDE). PDE is discretized such that the entire thickener is modelled as a number of vertical sections (cells) with the height of $\Delta x = L/J$ and $\Delta t = T/N$, where J and N are integers representing the number of cells and number of time-steps respectively. Let φ_j^n denote the approximate value of φ at (x_j, t_n) where $x_j = j\Delta x$, $t_n = n\Delta t$. With assuming initial conditions φ_j^0 for $j = 0,1,2, \ldots, J$, the discretized Eq. (1) is as follows:

$$\varphi_j^{n+1} = \varphi_j^n - \frac{1}{S_j}\left\{\frac{\Delta t}{\Delta x}\left[Q_D(t_n)\left(\varphi_{j+1}^n - \varphi_j^n\right) + S_{j+\frac{1}{2}} f_{bk}^{EO}\left(\varphi_j^n, \varphi_{j+1}^n\right) - S_{j-\frac{1}{2}} f_{bk}^{EO}\left(\varphi_{j-1}^n, \varphi_j^n\right)\right] - \frac{\Delta t}{\Delta x^2}\left[S_{j+\frac{1}{2}}\left(A\left(\varphi_{j+1}^n\right) - A\left(\varphi_j^n\right)\right) - S_{j-\frac{1}{2}}\left(A\left(\varphi_j^n\right) - A\left(\varphi_{j-1}^n\right)\right)\right]\right\} \tag{7}$$

Where:

$$a(\varphi) = -\frac{f_{bk}(\varphi)\ \sigma_e'(\varphi)}{\Delta\rho\, g\, \varphi}, A(\varphi) = \int_0^{\varphi} a\,(s)ds \tag{8}$$

$$f_{bk}^{EO}\left(\varphi_j, \varphi_{j+1}\right) = f_{bk}(0) + \int_0^{\varphi_j} max\{f_{bk}'(s), 0\}\ ds + \int_0^{\varphi_{j+1}} min\{f_{bk}'(s), 0\}ds \tag{9}$$

Incorporating the approximated boundary conditions given in Equations. (7) and (8), the process descriptions in the discharge ($j = 0$) and feed ($j = J$) are given as follows:

$$\varphi_0^{n+1} = \varphi_0^n - \frac{1}{S_0}\left\{\frac{\Delta t}{\Delta x}\left[Q_D(t_n)(\varphi_1^n - \varphi_0^n) + S_{\frac{1}{2}} f_{bk}^{EO}(\varphi_0^n, \varphi_1^n)\right] - \frac{\Delta t}{\Delta x^2}\left[S_{\frac{1}{2}}\left(A(\varphi_1^n) - A(\varphi_0^n)\right)\right]\right\} \tag{10}$$