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Modeling cake filtration under coupled hydraulic, electric and osmotic effects

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ABSTRACT

Pore blocking is considered to dominate the dewatering efficiency in filtration processes. Various engineering measures were adopted to promote the permeate flux of membrane filtration, e.g. electro-osmosis, flocculation and aggregation, membrane flush and pressure adjustment. A new model was proposed to address the coupling effect of hydraulic, electric and osmotic fields on cake filtration on the basis of thorough review on relevant researches. A moving boundary was configured to evaluate the time-dependent cake growth behavior. An instant mass balance was assumed valid at the cake–slurry interface, which was shown to reflect the experimental facts. The coupled governing equations were solved numerically by finite element method (FEM), and were validated by comparing with experimental results. The nonlinear constitutive behaviors of the filter cake under varied pressure head were further included in the models. FEM analysis indicates that the hydraulic conductivity and electro-osmotic coefficient of the formed cake are critical for the permeation flux. Correspondingly the pressure head and electrical potential gradient applied to the filtration system largely determine the separation efficiency. The filter cake (FC) formed in front of membrane filter contributes a lot to the reduction in solvent flux under certain dewatering conditions. Measures to improve the flocculation behavior of dispersible sludge were explained by the new model. Modifying the surface charge of sludge with polyelectrolyte is found to benefit the dewatering only within a limited time/leachate range, which was reported for the first time. Suggestions on cake filtration were provided according to our numerical simulations.

1. Introduction

Solid–liquid separation is commonly used in various industrial fields for the treatment of wastewater and the removal of suspending particles or indissolvable toxicants from liquid phase. Filtration separation has also found applications in pharmaceutics, biotechniques, smelters and bioreactors. The migration and enrichment of fine particles form arched structure with dense fabrics in the vicinity of filter medium. The permeability of the filter medium will be reduced dramatically due to the formed filter cake, demonstrating negative effect on the separation efficiencies and therefore requiring careful consideration in the industrial designs and operations. Failure to understand the basic principles of flow through compactible cakes has been linked to many industrial failures. It is fundamental for engineers to understand the compaction of the solid phase accompanied with variable flow rate [1].

Modeling of cake filtration and expression can be divided into several stages according to the reviewing comments of Olivier et al. [2]: (1) conventional modeling by Darcian approach; (2) conceptual modeling by assuming sludge as networked material and considering hydraulic conductivity as material properties; (3) multiphase modeling by separating each phase from the mixed sludge and deriving relevant rigorous mathematical equations individually [3]. Tiller and coworkers have proposed a series of models about the compaction of sludge during dewatering treatment on the basis of consolidation theory [1,4–6]. As indicated in literatures, the porosity of sludge at the shifting stage from filtration to expression was always assumed to be constant across the sludge cake. Although some recent studies experimentally investigated the distribution and variation of porosity of filter cake, the most interesting aspects of sludge dewatering are actually the moisture removal rate and the final moisture content [3,5,7–10].

The porosity change during infiltration (rather than the expression state) might be marginal according to the theoretical analysis of Lee et al. [1]. The time evolutions of the solid pressure across the cake were found to shift towards the filter medium, indicating a compaction action of filter cake along with the formation of skin layer during the filtration stage. Restated, their calculation was based on a special industrial application case of which a certain amount of sludge with uniform initial porosity was placed on the sludge treatment facility (e.g. belt filter press) instantaneously before starting the infiltration process. The initial thickness of the deformable sludge cake is a big value compared to that of the formed cake in membrane filtration. Even though, the period of

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time in which the porosity variation should be considered occupies only less than 1.5% of the overall filtration time for the wastewater treatment sludge [1].

The fouling of filter medium is so fundamental to the evaluation of the separation performance that various measures have been implemented to improve the permeate flux. The electrophoretic phenomenon was utilized by Bargeman et al. to proceed the dewatering efficiency of biological colloidal. It has been proved capable of maintaining a high permeate flux compared to some other researchers [11]. Electro-dewatering was also found effective to remove water from the sludge flocs, an electric field at 1200 V/m increasing the sludge concentration from 3 to 8%, equivalent to >60% water removal [12].

The surface charge (ζ potential) of sludge could change dramatically under complex solution and environmental conditions. Flocculating agents are ubiquitously applied to improve the settling behavior and filtration performance of sludge. A coupled model was proposed by Bhattacharjee et al. for concentration polarization and solute transport during filtration [13]. Despite capable of predicting the variations of ionic concentrations, flux and individual ion rejections, the assumptions about the surface characterizations of the filtration channel are too ideal to be extended to modeling cake filtrations. Chemico-osmotic pressure was found to be critical to the overall dewaterability of a biosludge by Curvers et al. [14]. Increase in the bulk ionic strength neutralized the surface charges and the related rheological effects, causing an increase in the final solid volume fraction [14]. Surface charge adjustment is known to ease the difficulty of sludge dewatering. However, little reference is available to account for this effect in the modelizations.

Cake filtration models have been continuously developed to account for the change in porosity and velocity of solid skeletons in expression filtration [7,14–16]. However, little work has covered: (1) electrophoresis/electro-osmosis, used to pertain high permeate flux in filtration [17–21]; (2) solute migration, e.g. toxicants contained in wastewater treatment sludge that threaten public health [22] and (3) surface charge of filter cake, modifiable by chemical additives in sludge flocculation. Electro-osmosis and chemo-osmosis are likely to dominate the filtration in these circumstances besides the classic pore-fouling mechanism. However, these features have not been found to be discussed in models that are particularly related to cake filtration. This paper was therefore aimed at developing a coupled model for cake filtration with regards to electric field, hydraulic pressure and chemo-osmosis. The hydraulic, electric and osmotic fields were all incorporated into the new model, describing the solute transport as well as the solvent flux. With a series of assumption, the cake filtration was simulated with moving boundaries existing at the interface between the dilute slurry and the deposited filter cake. Various factors were investigated regarding their influences on the growth in filter thickness and/or solvent flux.

2. Modeling theories

Darcy's law is generally used to predict flow through porous media with negligible solid velocity. On this theoretical basis, various formulas were developed to simulate the flow through filter cakes for filter designs or experimental interpretation.

2.1. Cake fouling mechanism and countermeasures

Classical membrane fouling models generally include pore blockage, pore constriction, or cake filtration. Theoretical and experimental studies of protein fouling and sludge dewatering have often confirmed a sequence of transition in fouling mechanism, namely the cake filtration, standard blocking and complete blocking, during the filtration [9,23–25]. The variation of the flux with time can be modeled with the following equation

$$\frac{d^2t}{dV^2} = k\left(\frac{dt}{dV}\right)^n \tag{1}$$

where t is infiltration time; V is the volume of leachate collected in the outlet boundary; k and n are the model constants indicating the pore clogging velocity.

The flow resistance increases rapidly while the filter cake (FC) grows thicker and denser in the course of cake filtration [2]. The above equation agrees well with the variation of flow resistance that is reported to be highly linear with pressure head in log–log scale for the protein fouling. The specific resistance follows the power law relationship used for the compressibility of filter cakes [26]

$$R' = k'(\Delta P)^s \tag{2}$$

where k' is a constant related to the size and shape of the particles within the deposit; R' is the specific filtration resistance (kPa s/m^2); P is the pressure head applied across the filter media (kPa). The cake compressibility, s, varies between zero for an incompressible layer to a value of 1 for a very highly compressible layer. Recent studies showed that the applied pressure has no impact on the permeate flux when extremely compressible materials were filtrated and when the pressure head was larger than a threshold value [1,27]. The formation of compact skin in filter cake was considered to be the main cause. This behavior can be reasonably explained by Eq. (2) as the resistance grows linearly with pressure head when parameter s approaches 1.

2.2. Perspective on hydraulic conductivity of cake at different fouling stages

Grenier divided the pore fouling into three major groups, e.g. the pore constriction, pore blocking and cake filtration [25]. The variation of hydraulic permeability k with time during these processes has been well accepted, but remains obscure since no mathematical equations were clearly related to the specific fouling mechanisms. The authors made efforts to build such relationship in this study. According to Darcy's law, the following equation can be produced

$$J_v = k\frac{\Delta P}{L} = k\frac{\Delta P}{L_0 + (V/\mathrm{CSR})} \tag{3}$$

where J_v is the permeate flux; k is the hydraulic conductivity (m/s); L_0 is the initial thickness of the deposited cake (m); V is the leachate volume (L); CSR is termed as the cake–slurry ratio which is to be discussed in detail.

First, we assume the deposited cake within time dt equals the overall permeate flux divided by the solid fraction ratio (cake/slurry ratio, CSR). Then differentiating the above equation and taking the reciprocal yields

$$\frac{dt}{dV} = \frac{1}{J_v} = \frac{L_0 + (V/\mathrm{CSR})}{\Delta P k} \tag{4}$$

Further differentiating with collected permeate volume V gives

$$\frac{d^2t}{dV^2} = \frac{1}{k\Delta P\ \mathrm{CSR}} \tag{5}$$

When permeability k is constant, the above equation results in a constant value, corresponding to the cake filtration mechanism when $V > V_s$. The remaining case ($V < V_s$) was discussed in the supplemental materials. V_s is the shifting value in permeate volume determined experimentally by plotting the $d^2t/dv^2 - dt/dV$ in graph. This relationship has been validated in the membrane filtration experiments on both protein and clay slurries [25,26].