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Continuous liquid extraction from saturated granular materials

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HIGHLIGHTS

- A two-dimensional differential equation similar in form to Richard's equation is derived and solved.
- Effects of capillary and adsorptive forces are taken into account in the model.
- Two dimensional pore saturation, pressure head and liquid flux distributions are predicted.
- Effects of rotation speed, inlet slurry flow rate and cone angle on extracted liquid fraction are investigated.
- The model can be used as a design tool for the development of continuous filtering centrifuges.

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ABSTRACT

A steady-state model for continuous extraction of liquid from saturated cake in a conical filtering centrifuge is presented in this work. The model describes unsaturated liquid flow through a cake of solid particles sliding along a conical screen basket. Effects of capillary and adsorptive forces are taken into account by using the liquid retention curve and the hydraulic conductivity function. Mass balance and the Darcy-Buckingham equations are used to develop a transport equation for the centrifuge similar in form to the Richards equation. The model is applied to predict extraction of molasses from sugar sucrose particles and can be applied in other applications where liquid is extracted from saturated granular materials. Distributions of pressure head, pore saturation, and drained liquid flux in the cake are predicted. Effects of cone geometry, rotation speed and mass flow rate on the fraction of extracted liquid are investigated. The model presented in this work can be used for the design of continuous filtering centrifuges and the prediction of optimal operating parameters in various applications.

1. Introduction

Conical filtering centrifuges are used for continuous extraction of liquid phase from solid particles. They have a variety of applications in the chemical industry. For example, they are used for the extraction of starch, salt, and low-protein fiber from grain, and the separation of sucrose crystal particles from molasses in the sugar industry (Wakeman and Tarleton, 2005). Conical filtering centrifuges are relevant to the development of a continuous process for non-aqueous extraction of bitumen from oil sand. In such a process oil sand is mixed with solvent to dissolve bitumen. Continuous filtering centrifugation would then be used to extract solvent-diluted bitumen from a cake of mineral particles. The development of a theoretical basis of continuous cake desaturation for the prediction of extracted liquid fraction is important for the design and performance evaluation of filtering centrifuges.

Swindells (1982) and Greig (1994) investigated experimentally and theoretically the performance of conical filtering centrifuges for the separation of sucrose crystal particles from molasses. A semi-empirical approach was adopted to describe centrifuge operation. Bizard and Symons (2011) developed a one-dimensional analytical model for continuous separation of sucrose particles from molasses based on equations of conservation of mass and momentum and interfacial friction equilibrium. The granular material was assumed to follow the Mohr-Coulomb yield criterion with zero cohesion. Thus, the cake was modeled as a rigid granular mass sliding along the screen under centrifugal force. The component of centrifugal force normal to the screen was the driving force for fluid drainage through the cake as it moved along the screen. Three distinct regions were modeled along the rotating cone: In region I, near the inlet of the cone, the flow was over-saturated and the cake of densely packed particles was immersed below a liquid layer. In region II the cake was desaturated as the liquid level dropped below the cake height. In this case, the top of the cake was damp and the bottom was saturated. In region III the granular cake was damp, with only residual liquid fraction left in the cake.

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Nomenclature

Roman symbols

a	tribology parameter for the shear traction of the cake along the screen (Pa.s/m)
d_p	particle diameter (μm)
g	gravity (m/s^2)
h	pressure head (m)
H_{cake}	cake thickness (m)
j	index for discretized radial position along the cone basket in r direction
i	index for discretized position along cake thickness in z direction
K	hydraulic conductivity (m/s)
k_s	saturated permeability (m^2)
l	unsaturated hydraulic parameter
m	unsaturated hydraulic parameter
$\dot{m}$	inlet slurry mass flow rate (kg/h)
M_{in}^{M}	liquid mass fraction in the input slurry
n	unsaturated hydraulic parameter
P_{tot}	total normal pressure in the cake (Pa)
P_{eff}	effective pressure in the cake (Pa)
P_l	pore liquid pressure in the cake (Pa)
Q_{cake}	convected volumetric flow rate of the cake: solid phase + void, $Q_{cake} = \frac{1-M_{in}^{M}}{(1-\phi)\rho_p}\dot{m}$ (m^3/s)
$Q_{l\ conv}$	convected flow rate of the liquid phase (m^3/s)
$q_{l\ porous}$	drainage flux of the liquid phase, also noted q (m/s)
$q_{l\ conv}$	convective flux of liquid phase (m/s)
q	drainage flux of liquid phase, also noted $q_{l\ porous}$ (m/s)
r'	local radial coordinate between r and $r + \Delta r$ (m)
r	radial coordinate along the cone (m)
r_{in}	radial position at the centrifuge inlet (m)
r_{out}	radial position at the centrifuge outlet (m)
u_s	slip velocity of the cake along the screen (m/s)
z	cake thickness coordinate (m)
$z_i^{layer}\big]_r$	thickness coordinate of the center of the layer i at position r (m)
$z_i^{drain}\big]_{r\leqslant r'\leqslant r+\Delta r}$	local coordinate of the center of the layer i between r and $r + \Delta r$ for the solution of the desaturation equation. It is equal to, $z_i^{layer}\big]_r$
$\Delta z^{layer}\big]_r$	thickness of the layer i at position r (m)

Greek symbols

α	cone angle
β	friction angle between the cake and the screen
γ	unsaturated hydraulic parameter (1/m)
η_l	fraction of extracted liquid
τ	shear stress in the cake (Pa)
ψ	internal friction angle in the cake
θ	volumetric liquid content in the cake
$\bar{\theta}$	average volumetric liquid content through cake thickness
θ_r	residual volumetric liquid content in the cake
θ_s	saturated volumetric liquid content in the cake, equal to the cake porosity $\theta_s = \phi$
ρ_p	solid particle density (kg/m^3)
ρ_l	liquid density (kg/m^3)
ϕ	cake porosity
ω	rotation speed (rpm)
δA	convective flow cross-sectional area normal to the r direction (m^2)
μ_l	liquid viscosity, (Pa.s)

In Bizard's work Darcy's equation in a centrifugal field was used to describe liquid drainage through the cake for both over-saturated (region I) and unsaturated (region II) flows. The model did not include the effects of capillary and adsorptive forces on liquid drainage through the unsaturated cake. Cake desaturation in region II was modeled by assuming that pore saturation changes abruptly from 1 to 0 as the liquid level recedes into the cake following Darcy's equation with constant saturated hydraulic conductivity. Thus, the evolution of pore saturation through the cake and along the screen was not predicted and the effects of capillary pressure and adsorptive forces on cake hydraulic conductivity were not accounted for. Predicted pore pressure in the liquid-saturated pores was positive inside the cake and would drop to zero if the screen hydraulic resistance was negligible.

In this work we focus on modeling liquid extraction from a cake having variable saturation in a conical filtering centrifuge. The effects of operating parameters on the fraction of extracted liquid are investigated. Over-saturated flow (region I) is not included in this model but could be incorporated in future work. Several model assumptions presented by Bizard and Symons (2011) are adopted in this work, including: momentum conservation equations for steady-state axi-symmetric slender centrifugal flow, Mohr-Coulomb granular material, and the tribology model used to describe the shear traction of the cake on the screen. Liquid and solid particles densities and cake porosity are considered constant. The main difference between this work and the Bizard and Symons model is that, in the present work, an unsaturated flow model is used to describe liquid extraction flow through the cake. The effects of capillary and adsorptive forces on liquid drainage are taken into account by using unsaturated flow parameters that describe the liquid retention curve and the hydraulic conductivity function. The combination of mass conservation and the Darcy-Buckingham equations results in a transport equation similar in form to the Richards equation (Hillel, 2004; Simunek and Nimmo, 2005; Khammar and Xu, 2017). This equation is used to describe flow through unsaturated cake in both regions II and III without a need to distinguish between them. Two-dimensional distributions of pressure head, pore saturation, and liquid flux in the cake are predicted. The model is demonstrated for sucrose crystal desaturation from molasses and results are compared with Bizard and Symons model predictions (Bizard and Symons, 2011). Effects of operating and design parameters on extracted liquid fraction are investigated.

2. Model development

Fig. 1 illustrates the operating principle of a conical filtering centrifuge. The centrifuge consists of a conical perforated basket with a smooth slotted screen oriented parallel to the flow and fitted to the inside of the cone to allow for liquid drainage and facilitate particle slippage. The feed slurry is introduced along the axis of the rotating cone. Centrifugal force drives the movement of the cake of solid particles along the basket and liquid extraction through the screen. Extracted liquid flux through the basket, when the cake is desaturated, is generally expected to decrease as the cake slides along the basket (Fig. 1). A spherical coordinate system is adopted where the radial coordinate r originates at the axis of the rotating cone and increases along the conical basket (Bizard and Symons, 2011). In most practical industrial applications, the radial coordinate r is significantly greater than the cake thickness H_{cake}. In this case, a "slender" centrifugal flow approximation can be used where convective and Coriolis accelerations are negligible