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Specific energy consumption of cake dewatering with vacuum filters

Manu Huttunen [a,*], Lauri Nygren [a], Teemu Kinnarinen [b], Antti Häkkinen [b], Tuomo Lindh [a], Jero Ahola [a], Vesa Karvonen [c]

[a] LUT School of Energy Systems, Lappeenranta University of Technology, 53850 Lappeenranta, Finland
[b] LUT School of Engineering Science, Lappeenranta University of Technology, 53850 Lappeenranta, Finland
[c] LUT School of Business and Management, Lappeenranta University of Technology, 53850 Lappeenranta, Finland

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ABSTRACT

The energy consumption of vacuum filtration operations in cake filtration depends on the properties of the cake, the filtration conditions applied, and the progress of the cake dewatering process. Operating a vacuum filter at a high pressure difference requires a high air flow rate and thus has high energy consumption. By taking the filtered solids content into consideration together with the power demand and energy consumed at a certain pressure difference level, it is possible to investigate the specific power demand and energy consumption relative to the filtered cake solids content. When the mother liquor in the void space of the filter cake is replaced by air, the flow rate of air through the cake increases, which has a dramatic influence on the specific energy consumption. In this study, dewatering of calcite mine tailings is investigated with respect to the specific power demand and energy consumption of vacuum generation calculated using the assumption of an ideal isentropic process. The results of this study demonstrate clearly that both the air flow rate and the specific energy consumption in dewatering increase sharply after a certain solid content of the cake is reached. The results suggest that pumping costs in vacuum filtration can be reduced substantially by allowing a slight increase in the residual moisture content of the filter cake.

1. Introduction

Vacuum filtration is a unit operation used in the dewatering of various mineral slurries such as calcium carbonates, phosphates and sulphates. Continuous vacuum belt filters are typically applied when the solids to be separated do not contain much fines, settle rapidly, and form a permeable cake that can be dewatered at a moderate pressure difference, or when the cake has to be (countercurrent) washed in the filter unit (Sparks, 2012a; Svarovsky, 2000; Tarleton and Wakeman, 2007). Vacuum filtration with belt filters is an energy intensive operation, partially due to the large volumes of air flowing through the pores and cracks of the cake, as described by Ripperger et al. (2012), and because of the leakage of air into the vacuum box, e.g., near the edges of the filter medium.

A simple way to simulate the operation of horizontal vacuum belt filters in a laboratory is to use a Büchner test apparatus that consists of a cylindrical slurry basin, on the bottom of which the filter medium is installed. The test unit is connected to a vacuum source and experiments are then performed batchwise under various conditions. In cases when the filter cake is not washed, the total filtration time is divided into two periods, namely, separation and drying, the latter of which is often referred to as dewatering. During the separation period, the filter cake is formed and liquid is filtered through the cake until the solid particles form a rigid structure. The height of the cake remains constant, provided that the material is incompressible – a condition that is often assumed in dewatering calculations and modelling (Condie et al., 2000), although not exactly true for real mineral slurries. The separation period can be described mathematically using cake filtration equations derived from Darcy's law (Darcy, 1856). Several properties of the slurry and solids, such as particle size distribution, particle shape, solid concentration and surface charge of the suspended solids, have an effect on the cake formation, and thus also on the flow of liquid through the cake (Besra et al., 2000; Fan et al., 2015; Sorrentino, 2002; Wakeman, 2007). Darcy's law and filtration equations derived from it don't take into account all these properties, thus the results of these equations can only be considered as indicative.

The purpose of the drying period is to remove liquid from the pores of the cake until the target moisture content of the cake is achieved. Removal of pore liquid opens flow channels for air to flow through the cake, which increases the air flow rate (as

* Corresponding author.
E-mail address: manu.huttunen@lut.fi (M. Huttunen).

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described, e.g., by Wakeman and Tarleton, 1990) and leads to high energy consumption of the vacuum pump. Due to the gradually increasing air flow rate through the cake, the energy consumption of the drying period can become very high relative to the corresponding moisture reduction.

Reduction of moisture content by vacuum filters usually requires less energy than thermal drying. Therefore, mechanical dewatering of the dryer feed is regarded as a primary method for reduction of the energy demand of the drying process (Kemp, 2015, 2012). However, there is a product-specific limit for the best obtainable dewatering result, i.e. irreducible saturation, which is the minimum saturation of the filter cake obtainable by an infinite pressure difference (Campbell, 2006). Heat is sometimes used in the filter unit to further improve the dewatering performance (see e.g. Kinnarinen et al., 2013; Lee, 2006; Peuker and Stahl, 1999, 2000; She and Sleep, 1998).

For a given porous system, the pressure difference required for removal of liquid from pores of different diameters can be approximated using the Laplace-Young equation (Besra et al., 1998a,b), which states that the pressure required to overcome the capillary pressure of a pore is inversely proportional to the pore diameter. This logically means that the largest pores of the cake are dewatered first (Condie et al., 1996). Additionally, decreasing the surface tension and increasing the contact angle have been reported to help obtain low moisture content of the cake (Tao et al., 2000), which is also in accordance with the Laplace-Young equation. However, in practical applications of vacuum dewatering of mineral filter cakes when the aim is to produce readily transportable and storable powders, it is rarely possible to avoid the need for subsequent thermal drying.

Energy consumption has been an important topic of discussion in filtration literature investigating membrane filtration (Blankert et al., 2007), centrifugation and consolidation (Chu et al., 2005), filter presses (Zhu et al., 2016) and mechanical dewatering in general (Lee, 2006). The objective of these previous studies has been to evaluate the operation of solid-liquid separation systems with respect to the mechanical energy requirement of liquid phase operations, which is significantly different from the issue of specific power demand and energy consumption of vacuum systems in which gases are evacuated from a space to create the driving force for separation.

The aim of this paper is to enhance knowledge about energy consumption of vacuum filtration, in particular energy optimization of vacuum filtration dewatering of slightly compressible mineral filter cakes. In addition to the experimental study, the principal theories of cake filtration, dewatering and vacuum pumping are introduced. The study focuses on the power demand and energy consumption of slightly compressible mineral filter cakes during the filtration and dewatering periods. Power demand and energy consumption are discussed from the perspective of the final solids content of the dewatered cake, and it is shown that elimination of the last removable pore liquid using vacuum filtration is a highly energy intensive operation.

2. Theory

2.1. Cake filtration equations

The average specific cake resistance α_{av} is calculated using experimental data and the integrated, reciprocal form of the Darcy equation (Eq. (1)) (Darcy, 1856). More discussion and calculation examples concerning the presented filtration equations can be found in the literature, for instance Ripperger et al. (2012), Svarovsky (2000), and Tien (2012). Integrated form of the so-called general filtration equation for constant pressure operation is given by:

$$\frac{t}{V_f} = \frac{\alpha_{av}\mu c}{2A^2\Delta p}V_f + \frac{\mu R_m}{A\Delta p}, \tag{1}$$

where t is time, V_f is the volume of filtrate, μ is the dynamic viscosity of the filtrate, c is the filtration concentration, A is the filtration area, Δp is the applied pressure difference, and R_m is the resistance of the filter medium. When Eq. (1) is solved with respect to α_{av} using the symbol a for the experimentally determined slope t/V^2 in the calculation and omitting the resistance of the filter medium, Eq. (2) applies for the average specific resistance of the cake:

$$\alpha_{av} = \frac{2aA^2\Delta p}{\mu c}. \tag{2}$$

The average porosity of the filter cake ε_{av} is calculated from the cake dimensions and the void volume of the cake (Eq. (3)):

$$\varepsilon_{av} = \frac{V_v}{V_c} = 1 - \frac{m_s}{\rho_s AL}, \tag{3}$$

where V_v is the void volume ($V_v = V_c - V_s$), V_c is the cake volume, V_s used in the calculation of V_v is the volume of suspended solids in the cake, m_s is the mass of solids, ρ_s is the density of solids, and L is the height of the cake.

2.2. Cake dewatering

Vacuum filtration creates a two-phase flow in porous media. Cake dewatering is done by displacing filtrate, in this case water, in the cake by an immiscible fluid (air in this case). The structure of a cake can be considered as a matrix of solid particles in a liquid and gas mixture.

When the liquid in the void space of the cake is water, the saturation S of the cake is defined as:

$$S = \frac{V_w}{V_v}, \tag{4}$$

where V_w is the volume of water in the cake, measured in experimental work by evaporating all the pore water off the cake in an oven.

To understand reduction of cake saturation by vacuum filtration, the capillary forces in the bed need to be considered. Surface forces affect at the interface of the two flowing fluids in contact inside the cake. The surface tension force acts at the interface between the liquid and the solid and retains liquid in the finer pores of the cake (Wakeman and Tarleton, 2005a).

The Laplace-Young equation (Eq. (5)) determines the pressure difference required to enable gas flow through the capillaries, i.e. the pores of the cake. This pressure difference is often referred to as bubble point pressure or threshold pressure and can be calculated from:

$$\Delta p = \frac{2\gamma\cos\theta}{r}. \tag{5}$$

In the Laplace-Young equation, γ represents the surface tension at the liquid-gas interface, θ is the contact angle between the liquid and the solid, and r is the pore radius.

The two immiscible fluids flowing through the medium form unique pathways, which change as the fluid saturation of the cake changes during dewatering. As the liquid saturation is reduced, the liquid pathways become discontinuous, the flow of the wetting fluid ceases, and the cake reaches the state of irreducible wetting fluid saturation.

Reduced saturation, S_R, is defined as:

$$S_R = \frac{S - S_\infty}{1 - S_\infty}, \tag{6}$$