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Local filtration properties of microcrystalline cellulose: Influence of an electric field

Jonas Wetterling, Tuve Mattsson, Hans Theliander *

Department of Chemistry and Chemical Engineering, Chalmers University of Technology, SE-412 96 Gothenburg, Sweden
Wallenberg Wood Science Center, The Royal Institute of Technology, Chalmers University of Technology, SE-100 44 Stockholm, Sweden

HIGHLIGHTS

- Electro-assisted filtration of microcrystalline cellulose was studied.
- Local filtration properties was measured during experiments.
- The influence of the electric field was described using an electrofiltration model.
- The electric field could be used to improve the filtrate flow rate.
- Influence of electric field exceeded the effect of modifying suspension conditions.

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ABSTRACT

Mechanical dewatering through filtration can be problematic for materials that form compressible filter cakes and that have high specific surface areas. For this reason, dewatering is expected to be a major process challenge in the development of biorefineries aimed at producing materials with these characteristics. This study investigates the use of electrofiltration to dewater one such cellulosic material: a mechanically-modified microcrystalline cellulose. The local filtration properties were investigated during dead-end electrofiltration. The electric field was shown to decrease filter cake growth, which thereby decreased the filtration resistance. The application of an electric field during filtration was shown to improve the filtration rate of the microcrystalline cellulose to a greater extent than could be achieved by making changes to the pH of the suspension. The influence of ohmic heating and electrolysis reactions at the electrodes were considered and the influence of electroosmosis and electrophoresis on the filtration operation was described by an electrofiltration model.

1. Introduction

Dewatering is an important step in many industrial processes, e.g. in the forest industry, mineral processing and wastewater treatment. Thermal drying is often preceded by a mechanical dewatering technique, such as filtration, in order to achieve an energy-efficient solid–liquid separation. Filtration can however be challenging for materials that form highly compressible filter cakes due to the high filtration resistances involved. The difficulties associated with mechanical dewatering on an industrial scale are also largely dependent on the external specific surface area of the solid material: an increase in external surface area increases the filtration resistance. The size of the filtration equipment, as well as the filtration time required, could therefore become unfeasible. Both the compressibility of the filter cake and high specific surface areas are expected to contribute to the challenges of filtration in the development of biorefineries aimed at producing materials such as e.g. microfibrillated cellulose.

The use of assisted filtration techniques could play a role in improving the energy efficiency of the production of this type of material by increasing the rate and extent of mechanical dewatering. Depending on the application, assisted filtration techniques using either thermal effects (Clayton et al., 2006), acoustic fields (Muralidhara et al., 1985; Smythe and Wakeman, 2000), magnetic fields (Stolarski et al., 2006) or electric fields (Iwata et al., 2013; Mahmoud et al., 2010) have been suggested. Pressure filtration in an electric field (i.e. electrofiltration) has been shown to have the potential of improving the filtration rate of hard-to-filter materials ranging from wastewater sludge (Citeau et al., 2012; Mahmoud et al., 2011; Olivier et al., 2015) to biopolymers (Gözke and

* Corresponding author at: Department of Chemistry and Chemical Engineering, Chalmers University of Technology, SE-412 96 Gothenburg, Sweden.
E-mail address: hanst@chalmers.se (H. Theliander).

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Nomenclature

A	filtration area [m^2]
c	mass of solids per unit filtrate volume [kg/m^3]
D	dielectric constant of liquid phase [–]
d	distance between electrodes [m]
d_γ	average path length of radiation [m]
E	electric field strength [V/m]
E_0	standard electrode potential [V]
E_c	electric field strength in the filter cake [V/m]
E_{cr}	critical electric field strength [V/m]
E_s	electric field strength in the suspension [V/m]
h	height of the filter cake [m]
i	electric current [A]
n_γ	number of γ-detector observations [–]
$n_{\gamma,0}$	number of γ-detector observations for the empty filter cell [–]
R_{fm}	electrical resistance of the filter medium [Ω]
R_m	flow resistance of the filter medium [m^{-1}]
T	temperature [K]
t	time [s]
$U_{applied}$	applied voltage [V]
U_{open}	open circuit voltage [V]
u_i	electrical mobility [$m^2/s\ V$]
V	filtrate volume [m^3]
V_{cell}	filter cell volume [m^3]
V_{eo}	filtrate from electroosmosis [m^3]
V_{ep}	electrophoretically transported material [m^3]
V_p	filtrate from hydraulic pressure [m^3]
v_d	drift velocity of electromigration [m/s]
z_i	ionic charge number [–]

Greek letters

α_{avg}	average specific filtration resistance [m/kg]
Δp_E	electroosmotic pressure [Pa]
Δp_H	hydraulic pressure [Pa]
ε_0	permittivity of vacuum [F/m]
ζ	model parameter: apparent zeta-potential [V]
μ	viscosity of fluid [Pa s]
$\mu_{\gamma,l}$	attenuation coefficient of the liquid phase [m^{-1}]
$\mu_{\gamma,s}$	attenuation coefficient of the solid phase [m^{-1}]
ϕ	local solidosity [–]
ϕ_c	filter cake solidosity [–]
ϕ_s	suspension solidosity [–]
$\phi_{s,0}$	initial suspension solidosity [–]

Posten, 2010; Hofmann et al., 2006; Hofmann and Posten, 2003) through a combination of electrophoretic and electroosmotic actions. Electrofiltration has therefore been shown to have the potential of decreasing the energy demand of solid–liquid separation by reducing the need for thermal drying (Larue et al., 2006; Loginov et al., 2013; Mahmoud et al., 2011).

The local conditions in the filter cell vary significantly during the electrofiltration of materials that form compressible filter cakes. Depending on the electrical conductivity of the fluid and solid phases, the strength of the electric field may vary greatly as a result of the solid content of the filter cake and/or the suspension. In spite of this, few studies have measured local filtration properties during electrofiltration (Saveyn et al., 2006). This study investigates the local filtration properties of a cellulosic material during one-sided dead-end electrofiltration. A mechanically-modified microcrystalline cellulose was used as a model material for cellulosic materials with high specific surface areas. The filtration behaviour was studied at different strengths of the electric field and the influence of electrokinetic effects, ohmic heating and electrolysis reactions is described using an electrofiltration model based on average filtration properties. The validity of the model is discussed using experimental measurements of the local hydrostatic pressure in the filter cake and the local solidosity of the filter cake.

2. Theory

2.1. Electrofiltration

Electrofiltration utilises the charge of particle surfaces to improve the filtration operation. In an electric field colloidal particles move through electrophoresis, thereby influencing (in this case) the growth of the filter cake (Moulik, 1971). The electric field also gives an electroosmotic flow, thereby resulting in an additional driving force for separation (Kobayashi et al., 1979; Yukawa et al., 1971; Yukawa et al., 1976).

In addition to electrophoresis and electroosmosis the electric field also results in a temperature rise in the filter cell due to ohmic heating. This ohmic heating is dependent on the strength of the electric field as well as the electrical resistance of the system: heating increases with current intensity and, for experiments at a constant applied voltage, thus increases for suspensions with a high electrical conductivity. Increasing the temperature in the filter cell will improve the filtration rate by lowering the viscosity of the fluid (Curvers et al., 2007; Weber and Stahl, 2002). The power demand of the electrofiltration operation will, however, be high and thus reduce the overall energy savings that may be made compared to thermal drying techniques (Larue et al., 2006).

During electrofiltration, electrochemical reactions take place at the electrodes. These reactions are influenced by the material that compose the electrodes as well as by ions in the suspension (Lockhart, 1983; Mahmoud et al., 2010). The electrochemical reactions at the anode are given by Eqs. (1) and (2):

$$2H_2O \rightarrow O_{2,(g)} + 4H^+ + 4e^- \quad E_0 = 1.23\ V \tag{1}$$

$$M \rightarrow M^{n+} + ne^- \tag{2}$$

whereas the electrochemical reactions at the cathode are given by Eqs. (3) and (4):

$$2H_2O + 2e^- \rightarrow 2OH^- + H_2 \quad E_0 = -0.83\ V \tag{3}$$

$$M^{n+} + ne^- \rightarrow M \tag{4}$$

where M is the electrode material and E_0 is the standard electrode potential of the reaction at 298 K. In order to prevent corrosion of the anode, the electrode material should be chosen so that its standard electrode potential is higher than that of water electrolysis. Anodes used for electrofiltration are therefore often either titanium meshes coated by mixed metal oxides (Citeau et al., 2012; Raats et al., 2002) or constructed of noble metals (Rabie et al., 1994; Saveyn et al., 2006).

The electrolysis reactions result in acidic conditions at the anode and alkaline conditions at the cathode. The formed ionic products also migrate in the filter cell due to electromigration, giving a pH profile between the electrodes (Larue and Vorobiev, 2004; Yoshida et al., 1999). The local pH in the filter cake may influence the filtration behaviour during electrofiltration by affecting the