Contents lists available at ScienceDirect

Food and Bioproducts Processing

journal homepage: www.elsevier.com/locate/fbp

In situ investigation of soft cake fouling layers using fluid dynamic gauging

Tuve Mattsson[*,1], *William J.T. Lewis, Y.M. John Chew, Michael R. Bird*

Department of Chemical Engineering, University of Bath, Claverton Down, Bath BA2 7AY, UK

ABSTRACT

Cake fouling is a phenomenon contributing to flux decline during cross-flow filtration. Its behaviour is also difficult to predict, especially for challenging separations where organic materials often form compressible cakes with a high resistance. In this study Kraft lignin was used as a model material for organic foulants in cross-flow microfiltration experiments, and a non-contact fluid dynamic gauging (FDG) technique in pressure-mode configuration was used to study the cake fouling layers in situ. A new and enhanced FDG equipment was used; enabling an increased accuracy of the fouling layer thickness measurements and capable of producing higher fluid shear stresses on the surface of the cake layer for strength measurements. Using FDG, very thin fouling layers were observed; in addition, FDG was used to investigate their cohesive and adhesive strengths, showing that over a 10-fold increase in fluid shear stress was required to remove foulant closer to the membrane compared with that on the surface of the cake.

Keywords: Fluid dynamic gauging; Microfiltration; Cross-flow filtration; Kraft lignin; Membrane filtration; Dewatering

1. Introduction

For solid-liquid separation, filtration is often the preferred method and is widely utilised in a range of industrial sectors. Advantages of filtration compared to other methods (such as drying) include a reduced energy consumption and a lower risk of thermal damage to the separated materials, which is of particular importance in food and beverage processing. Filtration can be run in several different modes; but membrane cross-flow filtration is particularly suitable for difficult-to-filter materials as the build-up of the high resistance filter cake on the membrane surface is counteracted by fluid shear imposed by cross-flow velocity (Belfort et al., 1994). Despite this, undesirable flux decline due to cake fouling is still one of the main issues in cross-flow filtration. Therefore a fundamental understanding of cake fouling phenomena, especially for difficult-to-filter organic materials, is crucial for the design of efficient separation operations.

The effect of fouling during cross-flow filtration is readily apparent and is often investigated by measuring the flux decline under a constant transmembrane pressure (TMP), or alternatively, by examining increases in TMP under constant flux operation. For an understanding of the underlying phenomena however, local properties need to be ascertained. One challenge presented in the investigation of cake fouling is the measurement of the thickness of the cake layer, which is preferably done in situ with limited disturbance to the layer. Chen et al. (2004) highlighted several existing non-invasive methods including Ultrasonic Time-Domain Reflectometry, Nuclear Magnetic Resonance, Laser Triangulometry and Direct Observation. A relatively new approach is Fluid Dynamic Gauging (FDG), which can estimate the thickness of cake layers during cross-flow filtration (Jones et al., 2012), and can also be used in a destructive mode to estimate local strength properties throughout the different layers of the cake (Lewis et al., 2012).

* *Corresponding author*. Tel.: +46 317723102.
E-mail address: tuve.mattsson@chalmers.se (T. Mattsson).
Received 30 June 2014; Received in revised form 1 September 2014; Accepted 9 September 2014
Available online 19 September 2014
[1] Present addresses: Department of Chemical & Biological 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.
http://dx.doi.org/10.1016/j.fbp.2014.09.003
0960-3085/

Nomenclature

Roman

d	inside diameter of gauge tube (m)
d_t	inside diameter of nozzle throat (m)
h	gauge height above a deposit (m)
h_0	gauge height above the membrane (m)
m_g	mass flow of fluid through the gauge ($kg\,s^{-1}$)
υ	cross flow velocity in the test section ($m\,s^{-1}$)
Δp	pressure drop over FDG nozzle (Pa)

Greek

δ	filter cake thickness (m)
μ	viscosity of the fluid (Pa s)
ρ	density ($kg\,m^{-3}$)
τ_w	fluid shear stress ($N\,m^{-2}$)

Acronyms

dP	differential pressure
FDG	fluid dynamic gauging
LVDT	linear variable differential transformer
TMP	transmembrane pressure

In this study, an enhanced FDG equipment is used to study soft cake fouling layers during cross-flow microfiltration of an organic model material, a Kraft lignin, which forms cohesive fouling layers and cakes which exhibit some degree of compressibility. Previous studies have concentrated on ultrafiltration under turbulent conditions (Jones et al., 2012), or microfiltration of near ideal particle suspensions (Lister et al., 2011). The use of lignin in this study demonstrates the complex behaviour of an organic material, which presents problems similar to those seen during the microfiltration of food based materials.

2. Experimental

2.1. Material

The model fouling material used in this study is a washed *Lignoboost*™ softwood Kraft lignin (Öhman et al., 2008); an organic substance that forms cohesive fouling layers. *Lignoboost*™ lignin is a chemically modified lignin precipitated under acidic conditions from the black liquor in the Kraft process and contains different phenyl propane structural elements. As Kraft lignin is known to be alkali-soluble (e.g. Öhman et al., 2007), the pH of the investigated suspensions was kept below 4 through addition of sulphuric acid to ensure that only precipitated lignin was present during experiments. The solid density of the lignin particles was measured at $1350\,kg\,m^{-3}$ using a gas pycnometer (AccuPyc II 1340, *Micromeritics*). The size distribution of the lignin suspension varied noticeably between experiments, and was characterised each time by laser diffraction (Mastersizer X, *Malvern*). Each experiment was performed with a total volume of 15 L of 0.02 vol% suspension in reverse osmosis water at pH 3.7 (adjusted using sulphuric acid) at ambient temperature (16–19 °C). The suspension was prepared right before each experiment from a stock slurry of 1–2 vol% lignin that had been stirred for at least 48 h to ensure sufficient dispersion.

The suspension was filtered using a hydrophilic regenerated cellulose membrane of 0.2 μm nominal pore size (RC58, *Whatman*), which was wetted prior to use. This pore size was selected so that all lignin particles were rejected by the membrane and cake formation was the predominant fouling mechanism.

2.2. Cross-flow filtration apparatus

The basic technique of pressure-mode fluid dynamic gauging is explained fully elsewhere (Lewis et al., 2012). Thickness measurements are performed by measuring the pressure drop through a nozzle, shown in Fig. 1 while a controlled flow of liquid, m_g, is drawn into it. The pressure drop is used to estimate the nozzle clearance, h at a known clearance, h_0. The thickness is thus indicated by $\delta = h_0 - h$. The apparatus used in this work was adapted and improved from that previously reported for cross-flow microfiltration by Lewis et al. (2012). Here, a smaller nozzle geometry (inner tube diameter, $d = 3$ mm, and nozzle opening diameter, $d_t = 0.5$ mm) was used, the dimensions of which are shown in Fig. 1. This conferred the following advantages over its predecessor:

1. Enhanced precision of thickness measurements.
2. Ability to study cake response to fluid shear stresses in excess of 50 Pa.
3. Smaller footprint in the flow cell.

This nozzle was mounted on to a purpose-built polycarbonate test section, a schematic for which is shown in Fig. 2. The test section housed a 250 mm flow channel of 15 mm square cross-section. A flat sheet membrane was mounted on to the bottom surface of this channel within a stainless steel cassette, which held it tightly against a porous spacer. The resulting flow cell within the test section contained a 150 mm × 15 mm porous surface set 1 mm lower than the rest of the flow cell, with tapered edges down to this point. The use of this setup allowed for facile removal of the membrane after experiments while avoiding loss of surface fouling. The bottom of the test section contained a small channel to collect permeate. The FDG gauge was positioned directly at the centre of the flow channel. The apparatus included two additional mounting points for the FDG apparatus such that the gauge could be positioned 60 mm upstream or downstream of this position. These locations were, however, not used in this work but would be useful for investigating any variation

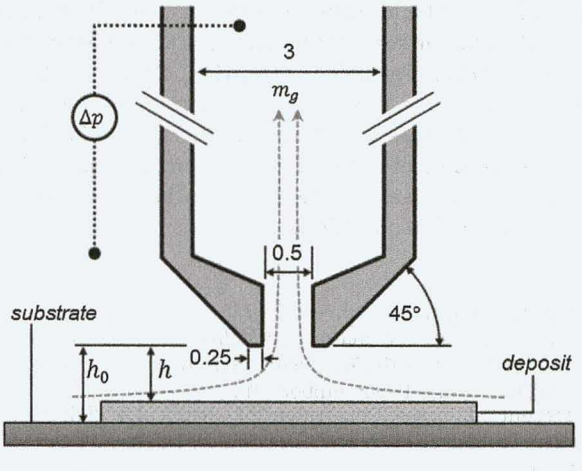

Fig. 1 – Schematic representation of the FDG nozzle, where Δp is used to indicate the clearance, h at an induced flowrate, m_g. Dimensions are in mm.