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Fluid dynamic gauging: A new tool to study deposition on porous surfaces

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Abstract

The deposition of fouling layers on porous surfaces such as those experienced in membrane/filtration systems has been investigated using the technique of fluid dynamic gauging (FDG). In this work, dead end micro- and macrofiltration processes were simulated using filter paper and glass ballotini suspensions. FDG was used to track, *in situ* and in real time, the build-up of a ballotini cake during the filtration process. The permeate flux through the filter paper was also simultaneously monitored.

Computational fluid dynamics (CFD) studies were performed to illuminate the fluid dynamics of FDG, with particular focus on the flow patterns and on the stresses imposed on the porous surface. The governing Navier–Stokes, Darcy's and continuity equations were solved using the Augmented Lagrangian Method implemented by the commercial partial differential equation solver, *Fastflo*™. The code was first tested successfully against previous studies in the literature featuring fluid flows in crossflow filtration tubular membranes, which had previously been solved by finite difference techniques. Simulations of gauging flow with a permeable gauged surface were then conducted and comparison with filtration experiments showed excellent agreement.

Keywords: CFD; Fouling; Membrane; Permeate flux; Thickness

1. Introduction

Membrane technology is used in many processes, exploiting their high selectivity, operation often without the need for additives and with relatively low cost and energy consumption. Of the two modes of filtration in common use, namely dead-end and crossflow filtration, it is generally accepted that crossflow mode is advantageous over dead-end operation [1].

Most membrane processes suffer loss of performance over time due to the deposition of unwanted fouling layers upon, or within, the membrane, causing declining permeate flux, increased operational cost, and shortened membrane life [2]. Fouling can occur from particles depositing on the membrane surface, macromolecules adsorbing onto the surface or into the bulk membrane material, or pore blocking. The increase in membrane fouling or resistance is manifested as a decline in the permeate flux. Design to mitigate or minimise fouling and promote cleaning is complicated by the variety of fouling mechanisms that can arise. Therefore, a fundamental understanding of fouling mechanisms is of paramount importance. Factors affecting membrane fouling include membrane type (such as membrane material, pore size and distribution and design of filtration unit), operating conditions (such as pressures, crossflow velocities and turbulence) and suspension or solution characteristics (such as nature of both solvent and solute and concentration of solute). Sheikhloleslami [3] summarised the techniques available to mitigate membrane fouling classified the methods into three categories, namely control of fouling, pretreatment technologies and design of anti-fouling membranes and modules.

Earlier studies have shown that the build up of membrane fouling layers occurs in two stages [4]. Firstly, the initial decline is attributed to pore-blockage or/and the rapid build-up of particle concentration near the membrane surface. The subsequent long-term flux decline is due to membrane fouling, where the permeability of the interface can be reduced by internal modification (i.e. pore blockage) or the growth of an external layer

Abbreviations: ALM, augmented lagrangian method; BC, boundary condition; CFD, computational fluid dynamics; EB, electrical balance; FEM, finite element method; N–S, Navier–Stokes

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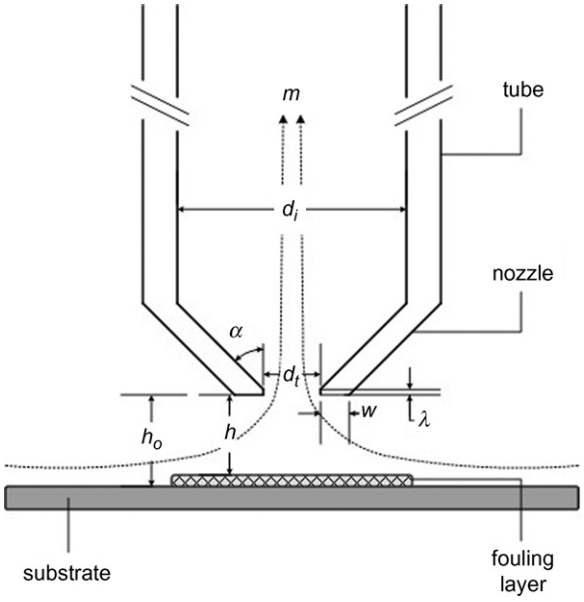

Fig. 1. Schematic of a typical gauging nozzle showing dimensions.

with associated resistance (gel layer or cake formation). These processes are often driven by the high concentration of solutes or suspended species at the interface resulting from rejection. Belfort et al. [5] have discussed the behaviour of suspensions and macromolecular solutions in crossflow filtration in great detail. Even more intense concentration polarisation and membrane fouling can arise in dead end filtration.

Various techniques have been adopted to monitor membrane fouling. *In situ* methods are preferable because they allow deposition or blockage to be monitored without moving the sample from its original position. Chen et al. [6] reviewed *in situ* techniques such as magnetic resonance imaging, refractometry, direct pressure measurements, etc., and broadly classified them as methods for studying concentration polarization and for cake formation and membrane fouling. Chen et al. [7] summarized the non-invasive observation techniques that utilized optical and non-optical probes. Another approach for characterising fouling is to measure the thickness of the filtration cake layer. *In situ* approaches include laser based optical methods [6,8,9], photo-interrupt sensors [10] and ultrasound [11,12].

Fluid dynamic gauging (FDG) is a relatively new technique developed to measure the thickness and deformation behaviour of soft fouling layers deposited on a substrate *in situ* and in real time [13]. The principle of the device is shown schematically in Fig. 1. The fouled test-piece is immersed in the liquid of interest and a nozzle is placed normal to, and close to the surface, so that the nozzle does not touch the surface but senses its presence. The technique exploits the flow characteristics of the liquid as it is drawn by suction through the nozzle and knowledge of the flow rate of the fluid going through the nozzle will provide information on the nozzle location in space which can allow one to calculate the location of the surface, and thereby any change in the deposit layers, δ, resulting from deposition or cleaning can be determined from $\delta = h_0 - h$. The detail of the theoretical development of this technique was discussed in [13].

The FDG technique has been shown to be a versatile and powerful technique for characterising the dynamics and mechanical behaviour of fouling layers on both hard and soft impermeable process surfaces. This paper describes the application of FDG to study permeable surfaces: FDG is used to monitor the filtration process of ballotini suspensions using filter paper, simulating a dead-end microfiltration application, *in situ* and in real time. FDG generates thickness information of the filtration cake and the permeate flux simultaneously, which are both key indicators of loss of membrane performance due to fouling, *in situ* and in real time. This work represents a proof-of-concept study demonstrating that FDG can be used to collect data on a rejecting permeable surface while it is operating. Rather than use a low permeability membrane with high pressure driving force, the authors opt for a high permeability membrane (filter paper) with a low pressure driving force as a convenient and cheap test system. The nozzle used in this work gives cake thickness measurements with an accuracy of $\pm 50\,\mu m$. A geometrically similar nozzle, with $d_t = 1$ mm and $d_i = 4$ mm, has been shown to give an accuracy of $\pm 10\,\mu m$. FDG devices for microfiltration applications would be designed to give at least this degree of precision.

2. Experimental

2.1. Apparatus

Fig. 2(a) is a schematic diagram of an FDG apparatus designed and constructed for the investigation of membrane fouling and cleaning behaviour. The apparatus consists of a Perspex tank (300 mm × 300 mm × 250 mm) and a nozzle connected to one end of a straight siphon tube of inside diameter d_1 (true length of the connected straight tube 0.42 m). The other end of the straight section is connected to a curved section with a smaller diameter, d_2 (true length of the curved tube is ∼1.0 m). The nozzle used is detailed in Fig. 1 with dimensions $d_t = 5$ mm, $d_1 = 20$ mm, $d_2 = 10$ mm, $w = 2.5$ mm, $\lambda = 0.5$ mm and $\alpha = 45^\circ$. The suction flow into the nozzle was driven by a fixed hydrostatic head, H, simply maintained by a siphon tube arrangement. The discharge flow rate as a function of suction head was measured by weighing the fluid collected from the discharge end of the siphon tube on an electronic balance (EB1: Precisa 8200 D SCS).

The spindle of the micrometer M1 (Mitutoyo, Japan) controls the vertical movements of the gauge, i.e. advancement or retraction of the siphon and the nozzle relative to the gauged surface. This arrangement allows the clearance to be set to a known distance. The apparatus also allows the gauge to traverse across the gauged surface to known locations using a traversing screw fitted with a vernier scale. This feature, however, was not employed in this study so the vernier scale has been omitted from the schematic.

Filter paper (Fisher Scientific, Code: FB59027) was used in this study to mimic a microfiltration membrane. Fig. 2(b) is an enlarged version of the Perspex cell near the gauging nozzle and shows a layer of filter paper clamped in position beneath a nozzle, separating the feed suspension or ‘feed side’ (liquid above