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A comparison of azimuthal and axial oscillation microfiltration using surface and matrix types of microfilters with a cake-slurry shear plane exhibiting non-Newtonian behaviour

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ABSTRACT

The mode of application of oscillation, axial or azimuthal, did not influence filtration performance, when filtering a calcite mineral with a d_{32} value of 2.7 µm. The equilibrium flux and deposit thickness correlated with shear stress, regardless of: filter type (metal slotted surface filter or homogeneous sintered filter); and mode of oscillation. Shear stress values up to 240 Pa were used and the particle compact believed to be at, or near, the deposited solids showed non-Newtonian flow behaviour described by the Herschel-Bulkley equation. The shear was computed using Comsol® to model the shear at, and near, the oscillating surface. The peak shear (maximum value) was used in the correlation for flux, which appeared to fit the data well and provide a realistic prediction for sustainable flux using a force balance model.

The existence of a yield stress in the compact appeared to limit the internal fouling of the matrix (homogeneous) type of filter, which had a membrane thickness of 8 mm, but did not demonstrate significant internal fouling over time, nor between filtrations. Thus, the results were similar to those obtained for the surface filters, and the resistance to filtration was dominated by the deposit formed.

1. Introduction

Microfiltration is used in a wide variety of process applications, and has had many years of academic investigation of factors influencing its operation and mathematical analysis of permeate flux [1]. Crossflow filtration is often applied due to its simplicity of design and operation. However, there are limitations in terms of the shear that can be obtained at the surface of the membrane, required to reduce the deposition of solids, and the inefficiency resulting from having to recycle the feed suspension over the membrane to provide economic operation. This recirculation, through what is often a high shear pump, can lead to the break-up of shear sensitive particles, e.g. flocs as well as sludge of a biological origin, generating finer particles which are more difficult to be filtered [2]. Hence, there has been increasing interest in Dynamic Filtration (DF), and enhanced shear microfiltration, where the shear at the membrane surface is not solely dependent on the crossflow rate, but is augmented by relative oscillation between the filter and slurry, or by rotation of the membrane, or surface close by [3].

There are a number of commercial, or semi-commercial, DF systems currently in use, or development [4]. The shear stress at the surface ranges from 0.35Pa to 39 Pa for these devices, when using the rheological properties of water to convert shear rate to stress. Oscillating azimuthal systems (VSEP, New Logic) are reported to show up to 17 times improvements in the permeate flux rate [3,4]. Rotating membrane discs (SpinTek) [5] have demonstrated dewatering from 5% to 15% during an endurance test of over 1500 h. Stationary membranes with rotating discs/impellers: DYNO; BOKELA; OPTIFILTER exist to enhance the shear at, or near to, the membrane surface. Other designs include: overlapping rotational membranes [6,7], overlapped counter-rotational membranes/impellers [8], helical rotating membranes [9–11], magnetically induced membrane vibrations [12], and axially oscillated hollow tube filters in membrane bio-reactors [13]. Filter designs that involve a moving membrane, or surface near to it, are more complex than simple crossflow systems, but they may provide a practical alternative to crossflow if they can sustain an appreciable flux and if they are less damaging to the material to be filtered. One potential application of such technology is in the nuclear industry, as part of reprocessing operations where the post-operational clean-out of reprocessing facilities, and the retrieval of waste from high-hazard "legacy" facilities, require the removal of particulate materials present at

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low concentrations in several effluent streams prior to conditioning (e.g. through encapsulation in cement) for long-term storage and disposal. For example at Sellafield, UK, iron oxyhydroxide flocs are precipitated by caustic dosing acid streams and then membrane filtered in order to remove transuranic species in the Enhanced Actinide Removal Process. Under these circumstances the ability to filter in a once-through (rather than recycled) system and, possibly, using a pump to suck the permeate through the membrane (avoiding pumping an abrasive suspension or one that breaks up within the pump) would be additional advantages, for example reducing the cost of providing containment and shielding and making the technology viable for small, mobile local effluent treatment plants.

Oscillations have been shown to have a greater effect on the shear at the surface of a filter than simple rotational systems [14,15], due to fluid inertia. There have been a number of academic studies of oscillating microfiltration [16,17]. In most cases the experimental approach has been to investigate Newtonian systems at low feed concentration. Many of these studies have used yeast suspensions [18] and algae [19], and reported the interaction of yeast fouling the membrane surface and pores. In most cases membrane blocking models have been developed [20]. Pulsatile flow at the surface of a membrane has been subjected to CFD analysis, but again due to the complexity of the problem this has been restricted to Newtonian systems [21]. It is the nature of fine colloidal suspensions that at the high solids content to be expected at, or near, the filter surface the rheological behaviour at the interface between the stationary membrane (or deposit) and the surrounding suspension will be non-Newtonian and may well exhibit a yield stress. This rheological behaviour will complicate the analysis of shear stress and application of microfiltration modelling.

The objectives of this study are to investigate a precipitated material filtering in different modes of oscillation (axial and azimuthal) on different structural types of filter (matrix and surface microfilters), and to model the non-Newtonian shear plane that will arise between the attached deposit on the filter and the surrounding feed suspension. The modelling should, therefore, be used to understand the correlation of shear stress and resulting permeate rates, from the application of a force balance. Different structural filter types could provide different fouled membrane performance.

2. Method and materials

2.1. Analysis of results

For the modelling of crossflow microfiltration a number of authors [17,22–25] have reported a linear correlation between equilibrium flux (J_e) and shear. In many cases the shear *rate* is used, which may be adequate for Newtonian and low concentration systems, but for more complex systems (where the location of the shear plane may be uncertain) the shear *stress* (τ), rationalised on the basis of a friction model approach, [1,26] is more appropriate as it is the drag force that removes particles from the surface of the filter:

$$J_e = K_1 x\tau + K_0 \tag{1}$$

where x is particle diameter is K_1 is dependent on the frictional forces and K_0 arises due to electrostatic repulsion and any other force that may act to keep the particles from forming a cake. Following a force balance approach it is possible [1] to investigate the frictional constant (K_1) further, leading to the following equation for flux, based on material and membrane properties:

$$\boldsymbol{J = \frac{\varphi^{2/5}}{\eta k_n \mu_w} x\tau} \tag{2}$$

where η is the frictional coefficient relating the normal and tangential forces, k_n is the constant in the Stokes drag equation and ψ is a dimensionless number [27] depending on the state of filtration. At the start of filtration:

$$\varphi = \frac{L_m}{R_m x^2} \tag{3}$$

where L_m is the membrane thickness and R_m is the membrane resistance, and after a cake has formed:

$$\varphi = \frac{k}{x^2} \tag{4}$$

where k is the permeability of the cake formed on the membrane surface. Permeability can be estimated by several expressions, a fundamental approach is that due to Happel and Brenner [28]:

$$k = \frac{\left(2 - 3C^{\frac{1}{3}} + 3C^{\frac{5}{3}} - 2C^2\right)}{\left(3 + 2C^{\frac{5}{3}}\right)} \frac{x^2}{12C} \tag{5}$$

where C is the solid concentration by volume of the cake formed on the membrane surface and x is a representative particle diameter within the filter cake. However, it is well known that cakes formed during microfiltration tend to contain finer particles than the initial feed distribution [1], due to the preferential shear removal of the larger particles. There is also evidence that even during conventional dead-end cake filtration the performance is dominated by the fine particles present, which can percolate and deposit at pore constrictions. Thus, it is recommended that for the purpose of filtration modelling of permeability the surface area to volume (Sauter mean) diameter is not necessarily used, instead the particle size corresponding to the 10%, or even 5%, on the cumulative mass undersize curve may be more representative [29].

In Eq. (2) the frictional coefficient relating the normal and tangential forces and the constant in the Stokes drag equation can be combined in to a single constant. The constant in the unmodified Stokes drag expression (Eq. (6)) has the value of 3, but this expression was derived for a single sphere in an infinite fluid. It is common to modify the Stokes drag expression to account for the influence of a wall, or other particles, on the drag experienced by the particle of interest. For the purpose of the modelling here it is proposed that the influence of the surrounding particles will have something in the order of increasing the drag by a factor of 100, compared to that predicted by Eq. (6), and in the absence of any knowledge of the friction coefficient a value of unity will be assumed. Hence, the combined constant (β) has a value of 300 for the product of: k_n and η. This value of the combined constants appears to be reasonable based on the above description, and will be shown to fit the experimental data.

$$F_d = 3\pi\mu x u_x \tag{6}$$

Eqs. (2) and (5) can be used to determine the shear stress required to avoid the deposition of particles on to the membrane surface. This was originally known as the critical flux concept, which later became 'sustainable' flux acknowledging the likelihood of some very limited, and remaining constant, fouling of the membrane [30]. The relation between the required shear stress and the sustainable flux (J_s) is [1]:

$$\tau >= \frac{\beta\mu}{x^{1/5}} \left(\frac{L_m}{R_m}\right)^{-2/5} J_s \tag{7}$$

During microfiltration the transmembrane pressure (ΔP) can be related to the flux in the usual way based on Darcy's Law:

$$\Delta P = \mu(R_m + R_c)J \tag{8}$$

where R_c is the cake resistance. It is possible to relate the membrane resistance to the permeability of the membrane (k_m) in the usual way:

$$R_m = \frac{L_m}{k_m} \tag{9}$$

For a homogeneous matrix type of membrane, i.e. one made of sintered, or randomly packed, material rather than a surface filter then the membrane permeability may be modelled as a packed bed. This can