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The critical pressure for microfiltration of oil-in-water emulsions using slotted-pore membranes

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ABSTRACT

The influence of fluid properties on the critical pressure of permeation of an oil micro-droplet into a slotted pore is studied numerically by solving the Navier-Stokes equations. We consider a long slotted pore, which is partially blocked by the oil droplet but allows a finite permeate flux. An analytical estimate of the critical permeation pressure is obtained from a force balance model that involves the drag force from the flow around the droplet and surface tension forces as well as the pressure variation inside the pore. It was found that numerical results for the critical pressure as a function of the oil-to-water viscosity ratio, surface tension coefficient, contact angle, and droplet radius agree well with theoretical predictions. Our results show that the critical permeation pressure depends linearly on the surface tension coefficient, while the critical pressure nearly saturates at sufficiently large values of the viscosity ratio or the droplet radius. These findings are important for an optimal design and enhanced performance of microfiltration systems with slotted pores.

1. Introduction

The efficient microfiltration of oil-in-water emulsions, that are commonly found in produced water from oil/gas recovery or as a by-product of metal finishing processes, is important for protection of the aquatic environment and recovery of clean water [1,2]. The advantages of the membrane filtration methods, as compared to sedimentation, dissolved gas flotation and centrifugation, include relatively low maintenance cost, mechanical stability and simple operating conditions [3–6]. The membrane separation process is based on rejection of non-wetting oil droplets that are larger than membrane pores, while at the same time allowing permeate flux, which is induced by the applied pressure across the membrane. However, the major practical challenge in achieving a high permeate flux is the membrane fouling [7]. Common antifouling strategies include crossflow filtration, physical or chemical cleaning, surface wettability modification, stabilization by surfactants, and electrostatic repulsion [8–13]. More recently, a multicontinuum approach for estimation of the permeation capacity of thin flat membranes with a broad distribution of pore openings was formulated for oil-water emulsions with different droplet sizes and then validated using the experimental data [14,15].

At the microscopic level, the critical transmembrane pressure required for an oil droplet to permeate into a membrane pore can be deduced from the analysis of the Young-Laplace pressure across curved oil-water interfaces inside and above the pore [16]. In the absence of crossflow, a simple model for the critical pressure of permeation of an oil droplet into a circular pore was validated via detailed numerical simulations [17] and experimental measurements [16]. As an aside, an analytical expression for the critical permeation pressure in the case of a continuous oil film above a membrane surface with a pore of arbitrary cross-section was obtained and validated for rectangular and elliptical pores [17]. It was later shown that in the presence of crossflow along the membrane surface, the critical pressure increases due to the drag force generated by the shear flow around an oil droplet, and, at sufficiently high shear rates, the droplet above the pore breaks up into two segments [17–19]. The results of numerical simulations have demonstrated that the breakup capillary number and the increase in critical pressure due to crossflow are nearly independent of the contact angle but depend strongly on the oil-to-water viscosity ratio, surface tension, and drop-to-pore size ratio [18]. Recent experimental studies on crossflow microfiltration have shown that membrane fouling might involve several stages, namely, droplet attachment and clustering, droplet deformation and coalescence [20] and that the critical flux decreases with salt concentration [21]. Using CFD modeling, it was also recently found that membrane fouling can be reduced by applying sufficiently large electric field, which results in the oil droplet

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detachment from the membrane surface [22].

One of the key factors for the efficient microfiltration of oil-in-water dispersions is the pore size and shape [23–27]. In particular, it was reported that, under similar operating conditions, the critical flux through a membrane with slotted pores is much higher than the flux through circular pore membranes [28]. This result can be intuitively understood from the fact that an oil droplet can only partially block a long slotted pore and thus allow a finite permeate flux, whereas a relatively large oil droplet completely blocks a circular pore. It was later shown that the experimental data for rejection of oil droplets by slotted pore membranes are well described by theoretical predictions, assuming that a spherical droplet deforms into an ellipsoid inside the pore and taking into account the static and drag forces [29]. An improved rejection of oil droplets through the slotted pore membrane can also be achieved by imposing vibration that leads to shear-induced migration and an inertial lift of droplets from the membrane surface [30]. Despite significant progress, however, the exact physical mechanism of the droplet permeation into a slotted pore even at the initial filtration stage and in the absence of crossflow is not fully understood.

In this paper, we investigate the process of oil droplet permeation into a slotted pore under applied pressure using numerical simulations and the Volume of Fluid method to track the oil-water interface. The critical permeation pressure is first estimated theoretically using a force balance analysis of the capillary forces and the drag force from the flow around the droplet. It will be shown that theoretical predictions agree well with the numerically obtained critical pressure as a function of the oil-to-water viscosity ratio, the surface tension coefficient, the contact angle, and the droplet radius.

The reminder of the paper is organized as follows. In the next section, the numerical simulation method and governing equations are presented. The theoretical prediction for the critical permeation pressure based on the force balance arguments is given in Section 3.1, and the results of numerical simulations and comparison with analytical predictions are reported in Section 3.2. The brief summary of the results is provided in the last section.

2. Numerical simulations

The interaction of an oil droplet with the porous membrane surface was studied numerically by solving the Navier-Stokes equation, which is implemented in the commercial software ANSYS FLUENT [31]. In turn, the dynamics of an oil-water interfaces was tracked by the Volume of Fluid (VOF) method, where computational cells contain information on the volume fraction of each phase [32]. More specifically, we considered an oil droplet at the entrance of a slotted pore and applied a pressure difference across the membrane, which induces a flow around the droplet, as shown schematically in Fig. 1. The numerical methodology for the problem of an oil droplet at a slotted pore is very similar to the numerical setup used in our previous papers, where the permeation, rejection and breakup of an oil droplet at a circular pore was investigated for a number of material parameters and various operating conditions [17,18]. In particular, we performed test simulations to determine the appropriate domain size and grid resolution necessary to accurately capture the effects of interface curvature and flow around the droplet. It was found that the computational domain has to be at least 4 times the size of the droplet and that at least 20 mesh cells are required across the pore. As discussed below, we considered an infinitely long slotted pore by using a symmetry boundary condition, thus eliminating the finite size effects due to pore ends. The numerical values of the geometrical and material parameters are listed at the end of Section 3.1.

In the Volume of Fluid method [32], the oil-water interface is specified by the volume fraction α, which is coupled to the flow via the solution of the transport equation as follows:

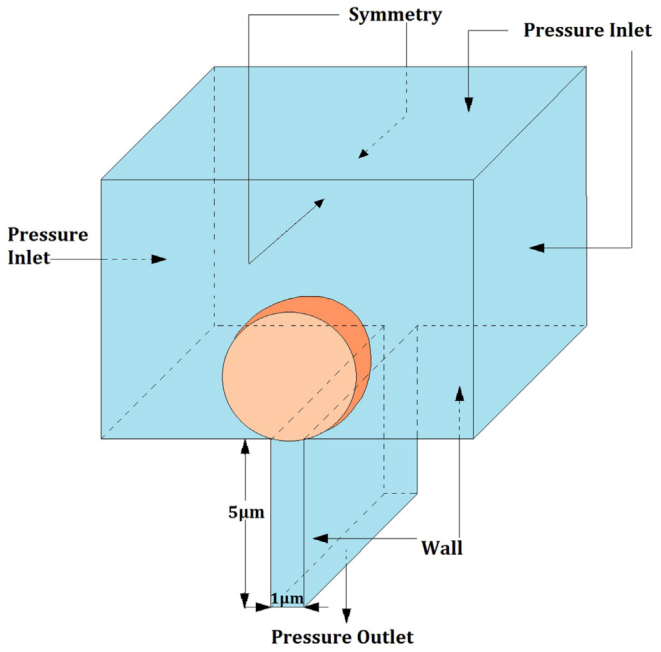

Fig. 1. A schematic diagram of the computational domain and the symmetry boundary conditions applied at the planes perpendicular to the membrane surface. The oil droplet is initially placed at the entrance of a slotted pore. The pressure inlet and outlet are applied above the membrane surface and at the bottom of the pore, respectively.

$$\frac{\partial \alpha}{\partial t} + \nabla\cdot\left(\alpha \mathbf{V}\right) = 0, \tag{1}$$

where $\mathbf{V}$ is the local velocity vector. The material properties near interfaces and in the bulk are averaged within each cell based on the volume fraction of each phase. For example, the averaged local density is obtained as follows:

$$\rho = \alpha\, \rho_2 + (1 - \alpha)\rho_1. \tag{2}$$

Next, the following momentum equation is solved numerically using the average fluid viscosity and density:

$$\frac{\partial}{\partial t}\left(\rho \mathbf{V}\right) + \nabla\cdot\left(\rho \mathbf{V}\mathbf{V}\right) = -\nabla p + \nabla\cdot\left[\mu\left(\nabla \mathbf{V} + \nabla \mathbf{V}^T\right)\right] + \rho\, \mathbf{g} + \mathbf{F}, \tag{3}$$

where $\mathbf{V}$ is the velocity vector, $\mathbf{g}$ is gravity, and $\mathbf{F}$ is the local surface tension force at the curved interface, which is defined as:

$$\mathbf{F} = \sigma\, \frac{\rho\, \kappa \nabla \alpha}{\frac{1}{2}\left(\rho_1 + \rho_2\right)}, \tag{4}$$

where κ is the local curvature of the oil-water interface and σ is the surface tension coefficient. The local curvature, κ, is computed as follows:

$$\kappa = \frac{1}{|\mathbf{n}|}\left[\left(\frac{\mathbf{n}}{|\mathbf{n}|}\cdot \nabla\right)|\mathbf{n}| - \left(\nabla\cdot \mathbf{n}\right)\right], \tag{5}$$

where $\mathbf{n}$ is the unit vector normal to the interface. Thus, the surface tension force given by Eq. (4) acts in the direction normal to the interface, and the magnitude of the force is larger for more curved interfaces [33]. Finally, the local orientation of the oil-water interface at the membrane or pore surfaces is determined by the static contact angle [34]. In practice, the unit vector normal to the interface at the solid surface is estimated as follows:

$$\mathbf{n}_i = \mathbf{n}_w \cos\theta + \mathbf{n}_t \sin\theta, \tag{6}$$