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Investigation of the critical entry pressure values associated with the permeation of an oil droplet through a cascade of pore throats and pore bodies: A quasistatic analysis

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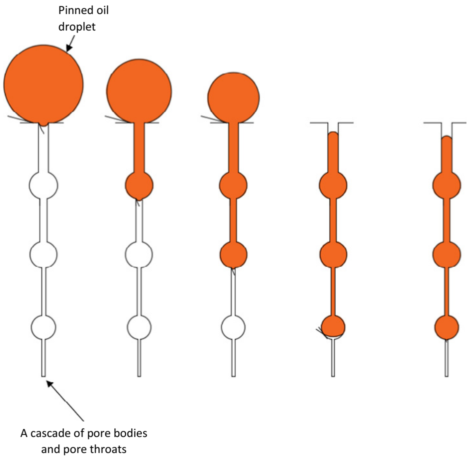
HIGHLIGHTS

- The filtration of an oil droplets through a cascade of pore bodies and pore openings is studied.
- The entry pressure formulae for the different possible configurations are obtained.
- A general formula, when part of the droplet is still at the surface of the membrane is obtained.
- This formula reduces to that found in literature, which determines the entry pressure for a pinned droplet.
- The permeation process is studied and investigated.

GRAPHICAL ABSTRACT



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ABSTRACT

In this work the problem of permeation of an oil droplet through a cascade of pore bodies and pore openings is investigated. When the oil droplet becomes totally within the pore cascade, it is called an oil ganglion. The cascade is considered composed of spherical pore bodies and cylindrical pore throats. The capillary entry pressure in relation to the applied pressure difference determines whether the oil ganglion will move or get trapped. Several cases are considered including the case when the leading part of the oil droplet is inside the cascade and the receding part is at the surface, the case when both the interfaces are within pore throats, the case when the two interfaces are within pore bodies, and the case when one interface is in a pore throat and the other is in the pore body. An algebraic equation has been developed to determine the entry pressure when part of the droplet is still at the surface of the cascade. This formula reduces to that found in literature when the whole droplet pins at the surface. This provides confidence in the developed relationship and the modeling approach. The entry pressure associated with all these cases is determined. Several examples have been considered to show how the critical entry pressure may vary throughout the cascade. It is found that, the influence of the receding part of the droplet at the surface of the membrane is not significant on the entry pressure formula. In other words, one can use the critical pressure formula associated with the leading interface to determine the breakthrough through the different parts of the cascade.

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1. Introduction

Wastewater containing dispersed oil droplets is a byproduct of many industrial processes. In particular, those industries related to petroleum exploration and production are known for their production of large volumes of oily-wastewater (Khatib and Verbeek, 2003; Fakhru'l-Razi et al., 2009; Munirasu et al., 2016; Dickhout et al., 2017). Such wastewater cannot be introduced directly to the environment because of its harmful effects to both the aquatic life and soil systems. On the one hand, oily-water can influence oxygen availability in the aquatic environment. In this case, dissolved oxygen will be depleted during the biodegradation process of hydrocarbons by bacteria. On the other hand oily-water can interfere with the absorptivity of soil materials to nutrients that are essential to the growth of plants and crops. It is important, therefore, to filter oily-water systems before they are introduced to the environment. In the recent years, membrane technology has been used extensively in the filtration processes related to oily-water systems. Two kinds of membranes have been used; namely ceramic-based membranes and polymeric-based membranes (Hu et al., 2016; Meng et al., 2012; Zhao et al., 2015). In particular, polymeric membranes have been used in filtrating oily-water systems for years (Ng et al., 2013; Harmant and Aimar, 1996; Chen et al., 2006; Deriszadeh et al., 2010). They are preferred by industry due to their low energy requirements, high removal efficiency and low operational costs. Polymeric membranes, on the other hand, suffer from some major drawbacks, which are related to the accumulation of oil droplets along the fabrics of the membrane. Several attempts have been made to find the optimal polymeric membrane materials suitable for oily-water filtration. In general filtration applications, the accumulation of particulate matters on or within the membrane internal structure degrades the performance of membranes with time. In oily-water filtration, the selectivity of the membrane is largely dependent on the existence of surface forces between different phases. It is required that oil droplets are nonwetting with respect to membrane materials to minimize their permeation and to ease their detachment. Unfortunately, normal polymeric membrane materials are not naturally nonwetting with respect to oil. Modifications of membrane materials have, therefore, been incorporated to change their affinity properties. This has been achieved, for example, through impregnating polymeric membranes with hydrophilic materials (Dolina et al., 2013; de Jubera et al., 2013; Radke, 2015). Such process has shown to be effective in the alteration of the physical and chemical properties of the membrane towards the incoming flux of oil droplets. Ceramic membranes, on the other hand, are, generally, made of inorganic-based materials including aluminum, zirconium, titanium, etc. (Wei and Li, 2009; Chen et al., 2013; Kujawa et al., 2016). They have advantages over polymeric membranes in that they have greater mechanical strength, tolerance to different pH, oxidation and temperature levels. Ceramic membranes are relatively new to the oily-wastewater treatment compared to polymeric membranes. Membranes with different percentage combinations of titanium, aluminum or zirconium have been tested for produced water treatment applications. These materials enhance the hydrophilicity of the membrane surface via bonding hydroxyl groups to the membrane porous structure. The hydrophilic nature of membrane material minimizes oil attachment at the surface of the membrane, thus effectively increases rejection capacity. Since, aluminum, titanium and zirconium-based membranes are relatively expensive, other low-cost modification methods (e.g., using fly ash) have been introduced. In addition, newer ceramic membranes have been made from zeolite-based materials, which exhibit ion separation capabilities. As mentioned earlier, porous membranes used to filter oily-wastewater systems rely on surface forces to resist the permeation of oil droplets. Surface forces identifies that there exists a threshold critical pressure that needs to be surpassed before an oil droplet may permeate. Therefore, if the pressure difference across the membrane is kept below the critical entry pressure, presumably, no oil droplets will permeate. Since porous membranes usually assume a distribution of several pore sizes, an overall criterion for the pressure that fulfills this requirement may not be achieved unless relatively low pressure difference is applied. This pressure, apparently, corresponds to the entry pressure of the largest pore sizes. Such low pressure, however, conflicts with the desirable requirement of higher permeation flux of filtered water. In other words, to keep the production of filtrated water at reasonable rates, relatively larger pressure difference across the membrane will require to be maintained. This implies that, the permeation of oil through the membrane is inevitable. One is, therefore, required to be able to estimate the permeation rates of filtered fluids through porous membranes under different operating conditions and the rejection capacities. The modeling of the different processes associated with the permeation of oil droplets through polymeric-type membranes has been the focus of extensive research work and several approaches exist, as will be explained in the next section. Microfiltration analysis indicated four fates for oil droplets in crossflow filtration. These; namely are, permeation, rejection, partial permeation, and pinning. Darvishzadeh and Priezjev (2012) constructed a fate map according to which it may be possible to identify the fates of oil droplets pinning at membrane surface according to four parameters; namely the transmembrane pressure, TMP, the crossflow velocity, CFV, the critical entry pressure, and the critical velocity. Such fate maps have been used extensively by Salama et al. (2017, 2018) and Salama (2018) to construct the multicontinuum approach to model the whole process. While this has been possible in thin membrane systems (e.g., polymeric-based membranes), the situation is more complex with respect to ceramic membranes. Oil droplets in addition of being subject to the previously identified fates, can also get trapped inside the membrane pore structure. This modifies significantly the analysis and requires, probably different treatment methodology. In this work, we investigate the problem of permeation of oil droplets through a cascade of pore throats and pore opening, to highlight the different configurations involved during this process and to estimate the entry pressure at different stages.

2. Modeling of oily-water filtration

Oily-wastewater systems exist as an oil-in-water emulsion in which tiny oil droplets are dispersed in the continuous water phase. The diameter of dispersed oil droplets ranges over a wide range, but they are usually on the order of tens of microns. A number of frameworks have been applied to investigate the problem of oily-water permeation through polymeric membranes. They can be categorized into four types; namely (1) the use of phenomenological relationships to estimate the permeation capacity of membranes (Hermia, 1982), (2) the use of computational fluid dynamic, CFD, techniques to study the accumulation process of oil towards the membrane surface (Tashvigh et al., 2015; Rahimi et al., 2005; Jalilvand et al., 2014; Pak, 2008; Lotfiyan, 2014; Wiley and Fletcher, 2003), (3) the use of CFD to investigate the physics involved during the microfiltration of a single oil droplet pinning at pore openings (Darvishzadeh and Priezjev, 2012), and (4) the use of the multicontinuum approach which upscales the findings of the microfiltration analysis to the membrane scale (Salama et al., 2017; Salama et al., 2018; Salama, 2018). While it was possible to investigate the permeation of oily-water systems through polymeric membranes, as described, using several frameworks, it may be difficult to apply such frameworks to ceramic