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Investigation of the onset of dislodgment of a nonpermeating oil droplet at a membrane surface: Standard models and a new force balance model

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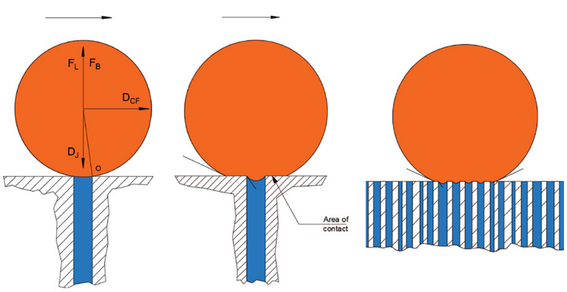
GRAPHICAL ABSTRACT



A droplet pinning over approximately a line | A droplet pinning over an area | A droplet pinning over multiple pore openings

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ABSTRACT

The need to determine the onset of dislodgment of an oil droplet pinning over a membrane surface is important in order to determine the critical conditions at which oil droplets detach. Although, previous studies considered this case in relation to an oil droplet pinning over a single pore, in reality, relatively larger size droplets pin over multitude of pore openings. In other words, droplets contact the surface over an area large enough to render the torque balance, which was devised previously to determine critical velocity, inaccurate. Another framework based on force balance is developed in this study from which critical velocity for the dislodgment of pinned droplet may be estimated. A friction force is assumed to balance the drag force due to crossflow field. The friction force is proportional to the resultant normal force that applies on pinned droplet. The proportionality factor is a friction coefficient that is determined as the ratio of the drag force due to crossflow and the resultant normal force. In this work, we determine these forces in addition to the crossflow velocity required to dislodge pinned droplet through computational fluid dynamic study (CFD). This analysis may be applicable to systems in which the deformation of the droplet is not large enough. In this case the resultant component of surface forces along the surface may be considered small. In this study a rectangular domain is considered with a 9 × 9 vertical tubes representing a pattern of pore openings. An oil droplet is released closer to the surface, where the permeation flux carries the droplet to reside on the membrane surface. The pressure inside the domain is adjusted such that it is less than the critical entry pressure and therefore, the droplet will not permeate. We seek to determine the velocity at the top surface that is barely enough to dislodge the droplet. This velocity, in addition to permeation flux, is used to determine the different hydrodynamic forces required to determine the friction force. In this study a number of droplets of different diameters are considered, namely 8, 10 and 12 microns. A base scenario is considered to determine the friction factor when no pores exist. A formula is suggested to

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estimate the friction factor for the more complex multipored system using that obtained when no pores exist. The numerical work is validated against the data exist in literature and excellent qualitative and quantitative match are obtained, which builds confidence in the numerical approach.

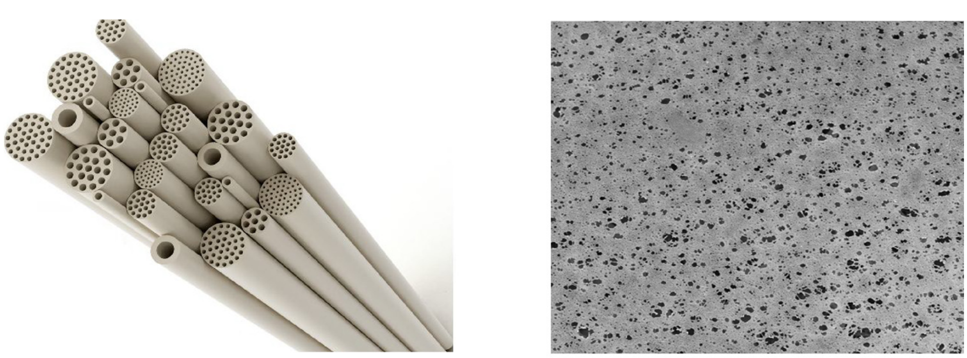
1. Introduction

The separation of two or more immiscible fluids has been the subject for comprehensive research, both theoretically and experimentally, because of its practical importance [1–11]. Many industries produce large volume of waste materials that are essentially a mixture of different immiscible fluids. The focus of the current study is the separation of oily-wastewater systems in which the oil exists as a dispersed fluid, in the form of tiny droplets, in the continuous water phase. Such oily water systems are byproducts of many industries including oil production, petrochemical, pharmaceutical, food industries and others. During the secondary phase of oil production, water is used to displace the oil towards production wells and is pumped with the oil to the surface facilities where larger percentage of the oil is separated from the water using physical methods. The separated water cannot be directly introduced to the environment because of the remaining oil content and other chemical constituents. It must go for further separation before safe disposal. Membrane technology has been lately the technology of choice for the filtration of produced water because of its apparent advantages of easy operational procedures, cost effectiveness, wide range of applicability to different emulsion properties, etc. Mainly two types of membrane technologies have been considered for the filtration of oily wastewater systems; polymeric-type and ceramic-type membranes. Fig. 1 shows typical ceramic and polymeric membrane. In general, ceramic membranes can resist variety of solvents, oxidizers and other chemical products across a wide range of pH and at elevated temperatures. Polymeric membranes, on the other hand, have been used extensively in gas separation processes.

The use of polymeric membranes in water purification applications necessitates that the affinity properties of the membrane towards water be improved. This has been improved by introducing hydrophilic groups to the surface of the membrane to form strong hydrogen bonds with water [12–15]. However, membrane technology is also prone to some disadvantages. Probably the most serious one is related to the inevitable deterioration of their performance with time due to fouling. The selectivity features of the membranes used in the filtration of oily-water systems rely on the utilization of capillary forces to hold oil droplets from permeating through membrane openings. Such capillary forces depend on the surface tension, contact angle, and pore and oil droplet diameters. Therefore, according to the applied transmembrane pressure, TMP, one can identify cutoff diameter of oil droplets for every pore size range above which oil droplets will not permeate. Since the membrane pores are not of a single size and likewise the oil droplet sizes, there will always be droplets of sizes smaller than the cutoff size. This means that the permeation of oil during the filtration is inevitable and needs to be quantified. It is important to find out such cutoff size of oil droplets associated with each pore opening in order to optimize the operating conditions according to the limits set by environmental authorities. The cutoff size of oil droplets can be determined by the analysis of the hydrodynamic forces affecting pinned droplets at the membrane surface. In this work we are particularly interested in a class of filtration processes called crossflow filtration. In crossflow filtration, the feed emulsion is forced to move along the membrane surface to reduce the potential of fouling development.

The crossflow field along the membrane surface generates a shear stress, which is aimed to help detaching pinned droplets and to get them dispersed back towards the main feed stream. In order to study this process in greater details two approaches have been adapted. The first is to devise experimental set ups to visualize the behavior of pinned oil droplets during crossflow filtration. While experimental methodologies may shed light on the behavior of the oily-water system under controlled conditions, the results cannot simply be extrapolated to other conditions or set ups. The second is to utilize the power of computational fluid dynamic (CFD) tools to explore this problem without going to the lab. However, for all the power that CFD provides, it cannot be used in large-scale systems because of the exhaustively large system of equations that are required to be solved simultaneously. In other words, CFD can be used to investigate smaller size systems to highlight the essential feature of the system during the filtration process. Other methods needed to be devised to upscale findings obtained by CFD such that integral variables suitable in the design process could be obtained. This has been the topic of the recently developed multicontinuum technique [16–18], which has been developed to utilize the details obtained by CFD analysis on a small scale systems and upscale it to model the entire membrane system.

The parameters of interest to a designer of an effective membrane system may be 1) the permeation capacity of the membrane, 2) the rejection rate of the dispersed material and 3) the rate of material buildup at the surface of the membrane. All these essential information can be obtained using the multicontinuum approach, which is essentially resting on accurate estimation of the criteria defining the fate of pinned oil droplets [16]. Historically, modeling approaches to the problem of filtration through porous membranes has gone through several advancements. As traditionally has been the case, they started with phenomenological description in an attempt to obtain macroscopic variables that are useful in the design process of efficient membrane



(a) (b)

Fig. 1. Ceramic and polymeric-type membranes (a) Ceramic membranes (membracon.co.uk); (b) SEM images of typical polymeric membranes (porexfiltration.com).