CHEMICAL ENGINEERING RESEARCH AND DESIGN XXX (2014) XXX–XXX

Contents lists available at ScienceDirect

Chemical Engineering Research and Design

journal homepage: www.elsevier.com/locate/cherd

Prediction of size distribution of crude oil drops in the permeate using a slotted pore membrane

A. Ullah[a,b,*], R.G. Holdich[a], M. Naeem[c], S.W. Khan[d], V.M. Starov[a]

[a] Department of Chemical Engineering, Loughborough University, Leicestershire LE11 3TU, UK
[b] Department of Chemical Engineering, UET Peshawar, KPK, Pakistan
[c] Department of Chemistry, AWKUM, Mardan, Pakistan
[d] Department of Civil Engineering, UET Peshawar, KPK, Pakistan

ABSTRACT

Size distribution of crude oil drops in the permeate has been predicted using the 'linear fit' approach with, and without oscillating the membrane. Without membrane oscillation (without shear rate), static and drag forces are taken into account and their balance is assumed as 100% cut-off or rejection point. With the membrane oscillation, 'inertial lift' model available in the literature is considered and in this case 100% cut-off is assumed when away migration and convection velocities becomes equal. Three types of crude oil drops with different °API values and interfacial tensions are analysed experimentally, the results are compared with the presented model and the model is an agreement with the experiments. The study has been validated with the genuine size distribution of oil drops obtained from oil companies operating at Kuwait at various locations in order to investigate the industrial applicability of the model. Overall oil concentration of the permeate can be calculated using the proposed model that provides an idea whether the concentration of oil in the permeate is within the standard set by international regulatory authorities.

Keywords: Prediction of permeate size distribution; Slotted pore membranes; Deforming crude oil drops; Microfiltration; Membrane oscillation; Permeate concentration

1. Introduction

Oil in water is associated with many environmental problems and needs to be separated efficiently. It is a threat for life in water and the concentration of oil in the seawater is limited to 30 mg l^{-1} or below (Kosvintsev et al., 2007). Initially, hydrocyclones were used as primary separators, but the separations targets for drops below 40 μm were not achieved and the process was too expensive (Colman and Thew, 1983; Hargreaves and Silvester, 1990; Wolbert et al., 1995).

In recent years, membrane separation technology has largely attracted researchers for oil/water separation (Shu et al., 2006). Ultrafiltration is useful with low oil content, but a lower permeate flux rate was achieved, normally lower than 100 l m^{-2} h^{-1}; which is too low to be commercially attractive for offshore operations (Lin and Lan, 1998; Lipp et al., 1988). Microfiltration is an efficient process for oil/water separation with drops below 10 μm and due to several advantages like: low space requirement, high permeate flux and high permeate quality; therefore, microfiltration is distinct from other membrane separation techniques used (Pan et al., 2007; Gryta et al., 2001; Cui et al., 2008; Scott et al., 1994; Mueller et al., 1997). Surface microfiltration is found effective than depth microfiltration because the membrane used in surface microfiltration can be cleaned easily after the process (Kuiper et al., 1998). Pore structure design has attracted researchers and circular pore membranes with surface filtration filters are found efficient in oil/water separation (Kuiper et al., 1998). Slotted pore membranes were found less foulent and higher permeate flux and better separation of filtering material were achieved

* Corresponding author at: Department of Chemical Engineering, Loughborough University, Leicestershire LE11 3TU, UK. Tel.: +44 7546983593.
E-mail addresses: A.Ullah@lboro.ac.uk, asmatuet@gmail.com (A. Ullah).
Received 21 March 2013; Received in revised form 16 December 2013; Accepted 13 February 2014
http://dx.doi.org/10.1016/j.cherd.2014.02.017

Nomenclature

F_c	static force (N)
F_d	drag force (N)
h	half width of the slot (m)
k_w	drag force correction factor
R_{sp}	radius of spherical drop (m)
v'	convection velocity of drops towards membrane surface with shear rate applied (m s^{-1})
v_{if}	inertial lift migration velocity (m s^{-1})
v'_0	convection velocity of drops towards membrane surface without shear rate applied (m s^{-1})

Greet symbols

σ	interfacial tension (N m^{-1})
α	angle at which slot converges towards inside (°)
ρ_f	density of the fluid (kg m^{-3})
γ	shear rate (s^{-1})
γ_{cr}	critical shear rate (s^{-1})
η	viscosity of the fluid (Pa s)

specially with deforming oil drops as compared to circular pore membranes (Ho and Zydney, 2006; Ullah et al., 2012a,b,c, 2011, 2013a,b).

Shear rate over the membrane surface is provided at higher fluid velocity in crossflow microfiltration that reduced fouling of the membrane (Scott et al., 1994). Crossflow microfiltration is very expensive and more energy is required for pumping the fluid again and again into the system (Sarrade et al., 2001; Jaffrin, 2008). Shear enhanced dynamic microfiltration is an alternative to crossflow microfiltration, in which shear is produced due to vibrating/rotating the membrane and the process is more economical (Jaffrin, 2008). Four times lower transmembrane pressure is observed by vibrating the membrane with 21 Hz during filtration of deforming oil drops (Ullah et al., 2012c, 2011). Similarly, vibrating the membrane increased separation efficiency of crude oil drops from water and separation increased linearly with increasing vibrating frequency of the used membrane (Ullah et al., 2013a).

Overall oil concentration in the permeate is an important factor and it has to be below the required standard set by international regulation authorities for oil content in water if the permeate is discharge into sea waters. Predicting size distraction in the permeate provide an opportunity to calculate overall oil concentration in the permeate at various flux rates and different interfacial tension systems with, without oscillating the membrane. The study provides a model for predicting size distribution in the permeate for a 4 μm slotted pore membrane and the presented model in the paper can be extended for membranes with different slots widths when different filtering both deforming and non-deforming particles.

2. Theory

Static force (F_{cx}) is the force responsible for the rejection of drops through the membrane without shear applied to the surface of the membrane and can be expressed as follows: (Ullah et al., 2012a, 2013b),

$$F_{cx} = -\left(2\pi R_{sp}\sigma\left(\left(\left(\frac{2h}{R_{sp}}\right) + \left(\frac{-3(h/R_{sp})^3 - \arccos(h/R_{sp})^3 \frac{1}{2\sqrt{1-(h/R_{sp})^6}}(-8(h/R_{sp})^6 + 2)}{\left(h/R_{sp}\sqrt{1-(h/R_{sp})^6}\right)^2}\right)\right)\right)\right) \times \sin\frac{\alpha}{2} \quad (1)$$

where σ is the interfacial tension between oil/water, R_{sp} is the radius of the drop, and h is the half width of slot of the membrane.

The drag force exerted on a sphere moving between two plates is given in (Kosvintsev et al., 2007; Soubiran and Sherwood, 2000) as:

$$F_d = k_w 12\pi\eta R_{sp} U \quad (2)$$

where k_w is a wall correction factor and for a similar system its value is equal to 4.3 (Kosvintsev et al., 2007). η is viscosity of the fluid, R_{sp} is the radius of the spherical droplet and U is the velocity of the fluid through the slot. The drop is under steady state conditions inside the pore, when F_{cx} becomes equal to F_d and the drops will be captured in this position. The drop will deform and will pass through the membrane when $F_d > F_{cx}$ and it will be rejected by the membrane in the case of $F_d < F_{cx}$ (Ullah et al., 2012a, 2013b).

When shear is applied (whether the applied shear is due to crossflow velocity or oscillating the membrane) to the membrane surface there is a lift present in the system, and due to the lift, drops moves away from the membrane surface (Hudson, 2003). Lift due to crossflow velocity through the membrane is referred as 'Inertial lift'. The model available in the literature for 'Inertial lift' is used as a starting point knowing the fact that the system used in the study is oscillating flow system and a higher lift might be present. Inertial lift migration created due to applied shear rate that opposed permeate velocity (Belfort et al., 1994). Migration velocity under fast laminar flow (the model is used as a starting point) conditions of a drop due to inertial lift, v_{if}, was deduced in (Belfort et al., 1994):

$$v_{if} = \frac{0.036\rho_f\gamma^2 R_{sp}^3}{\eta} \quad (3)$$

where ρ_f is density of the fluid, η is viscosity of the fluid, γ is the applied shear rate and R_{sp} radius of the drop.

Dilute oil/water emulsion is used, so, particle to particle interaction is assumed to be negligible in this case. Inertial lift velocity can be calculated using Eq. (3). Migration velocity (v_{if}) and convection velocity (v'_0) due to the drag created by flowing liquid acts in opposite direction and can be expressed as follows:

$$v' = v'_0 - v_{if} = v'_0 - \frac{0.036\rho_f\gamma^2 R_{sp}^3}{\eta} \quad (4)$$

This expression is used for comparison with the experimental data.

For a given shear rate and convection velocity or superficial velocity (v'_0), critical drop size would be the one at which v' becomes negative. Critical radius can be obtained using Eq. (4). For a given convection velocity, critical radius of drops would