Separation and Purification Technology 144 (2015) 16–22

Contents lists available at ScienceDirect

Separation and Purification Technology

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

Membrane oscillation and oil drop rejection during produced water purification

A. Ullah [a,b,*], M. Habib [b], S.W. Khan [c], M.I. Ahmad [b], V.M. Starov [a]

[a] Department of Chemical Engineering, Loughborough University, Loughborough, Leicestershire LE11 3TU, UK
[b] Department of Chemical Engineering, University of Engineering & Technology Peshawar, Pakistan
[c] Department of Civil Engineering, University of Engineering & Technology Peshawar, Pakistan

ARTICLE INFO

Article history:
Received 23 September 2014
Received in revised form 29 December 2014
Accepted 17 February 2015
Available online 23 February 2015

Keywords:
Produced water
Membrane oscillations
Particle rejection
Slotted pore membranes
Deforming oil drops
Microfiltration

ABSTRACT

Removal of crude oil droplets from produced water has been evaluated using a Nickel membrane with a slotted pore width of 4 μm and length of 400 μm. The membrane was oscillated at different frequencies that resulted in variable intensity shears at the membrane surface. The influence of membrane oscillations on oil droplet rejection was investigated and reported in this work. Membrane oscillations generated a lift for the surrounding particles which led the drops to move away from the membrane surface. Measurements have shown that the intensity of the droplet lift was linearly proportional to the intensity of the applied shear. Inertial lift velocity model reported in literature was used as a starting point which was coupled with the fluid's convection velocity. The model predicted 100% cut-off points through the membrane at various oscillation frequencies. Without the applied shear rate, the static and drag forces balanced each other, which was assumed to be the 100% cut-off point. With the applied shear rate, the inertial lift and convection velocities become equal and this point was referred to as 100% cut-off point. Overall mass of crude oil droplets in permeate flow was calculated knowing the 100% cut-off point and interfacial tension between the dispersed and continuous phases.

1. Introduction

The occurrence of oil droplets in water is a severe environmental problem posing significant threats to life within waters. The existence of oil in water is however attributed to various essential human activities such as the drilling and extraction of mineral oil and gas, food processing, and pharmaceutical manufacturing. Among all the activities the oil and gas industry is the biggest source of generating oil in water. Water coming from oil and gas platform contains oil droplets along with other chemicals, salts and metals. This oil contaminated water is commonly referred to as 'produced water' [1]. There are various disposal methods for this produced water, the common one being its discharge into the sea water or re-injection into the well for enhanced crude oil/gas production/recovery [2]. The reported maximum concentration of crude oil in produced water that is used for injecting into the oil wells and/or discharging into the sea is reported to be 10, and 30 ppm respectively [3]. Various physical, chemical, biological and membrane based techniques are currently available and are used for produced water treatment to remove the oil from water. However the high operational costs, usage of toxic chemicals, production of activated sludge has resulted in significant disadvantages for the use of chemical and biological treatment techniques due to their environmental un-friendliness and partially due to the requirement of comparatively big space for installation [2]. Physical separation techniques such as gravity separation and hydro-cyclones were found to be ineffective with oil drop sizes below 40 μm [2]. The use of membrane technology could be potential benefit in comparison with other conventional techniques to remove oil droplets from the produced water mainly due to the following distinct advantages [1]:

a. Low space requirement for equipment installation.
b. Physical separation thus requiring no chemical additives.
c. Environment friendliness.
d. Low input energy.
e. High permeate quality.

Various types of membranes are being investigated to remove the oil droplets from produced water. Studies on the use of ultrafiltration membranes were successful in the removal of oil from water however, the permeate flux was too low ($100\,\mathrm{l\,m^{-2}\,h^{-1}}$),

* Corresponding author at: Department of Chemical Engineering, Loughborough University, Loughborough, Leicestershire LE11 3TU, UK.
E-mail addresses: A.Ullah@lboro.ac.uk, asmatuet@gmail.com (A. Ullah).

http://dx.doi.org/10.1016/j.seppur.2015.02.022
1383-5866/

Nomenclature

a	membrane oscillation amplitude (m)
D	membrane diameter (m)
F	membrane oscillation frequency (Hz)
F_{cx}	static force (N)
F_d	drag force (N)
h	half of the slot width (m)
k_w	wall correction factor
R_{eo}	oscillatory Reynolds number
R_{sp}	radius of the drop (m)
U	in-pore/slot velocity (m s^{-1})
v_{if}	inertial lift velocity (m s^{-1})
v_o	velocity amplitude (m s^{-1})
v'	net velocity (m s^{-1})
v'_0	convection velocity (m s^{-1})

Greek letters

σ	interfacial tension (N m^{-1})
π	pi (3.14)
η	viscosity (Pa s)
υ	kinematic viscosity (m s^{-2})
ω	angular frequency (s^{-1})
ρ_f	fluid density (kg m^{-3})
α	angle at with the membrane slot converges inside (^{0})
$\dot{\gamma}$	shear rate (s^{-1})

making it unattractive for commercial application [4,5]. A high permeate flux (150 lm^{-2} h^{-1}) could be achieved with microfiltration membranes [6] and hence the use of surface micro filters is currently preferred over the conventional depth filters for oil/water separation [4]. The use of depth filters resulted in internal fouling due to the inherent torturous flow paths and as a result needed to be replaced prematurely [7]. The use of surface micro-filters, on the other hand, retained material on the membrane surface and as a result could be easily cleaned with back-flush water [4].

The membrane pore structure is considered as an important operational parameter that can influence both permeate flux and the rejection efficiency [8,9]. In circular pore membrane, a pore size equivalent drop can completely block the membrane [10]. The main reason being the resting over of circular drop on the pore entrance thus, completely blocking the way and as a result the entire trans-membrane pressure is used to deform and pass the droplet through the membrane pore [6], resulting in energy wastage. On the other hand, in slotted pore membranes, the oil droplets will partially block the slotted pore geometry and the drag force around the drop will be responsible for the passage and deformation of drop through the slots [11–16]. The inherent nature of slotted pore structure results in decreased rate of fouling in comparison with circular pore membranes and has thus proved to provide much higher permeate flux rates. Also, a better oil droplet rejection rate through slotted pore micro-filter structures is reported [11–16].

In cross-flow filtration systems, fluid flows over the membrane surface creates shear that reduces fouling of the membrane [17,18]. A high fluid velocity is required for the generation of significant shear over the membrane surface [19]. Cross-flow filtration is an energy extensive process and much of its energy input is consumed in recirculation of the fluid into the system [19]. One major disadvantage of this system is the potential damage to the shear sensitive materials in the operational process. To overcome this disadvantage, other shear induction techniques such as oscillation and/or rotation of the membrane at various frequencies [20,21] are being explored. This also gives an added advantage of energy efficiency [22] in comparison with high velocity flow to induce excess shear for oil drop migration through the slotted pore. Various mechanisms exist for the control of membrane oscillation, the common one being the use of pneumatics. The pneumatic control allows the shear to be induced on the membrane surface as required by increasing or decreasing the air flow to the vibrator. These membrane oscillation systems are extensively used for the removal of oil drops from water [11–16] and the increased rate of permeate flux is reported [23,24]. This resulted in increased membrane separation efficiency which requires four times less trans-membrane pressure in comparison with the use of non-oscillatory membranes for the same duty.

The main focus and objective of this study was to investigate the influence of membrane oscillation frequency on the oil droplet rejection with various flux rates. The crude oil drops in the produced water were passed through a slotted pore membrane at various filtration velocities and shear rates and their effects on the passage of deformation were investigated. The results have shown that in the absence of membrane oscillation, the static and drag forces were predominantly responsible for the rejection and passage of oil droplets through the slotted pore membrane. With membrane oscillation the influence of lift velocity is substantial and hence was taken into account to upset the convection velocity. The presented model can be used for estimating the overall concentration of oil in the permeate flow, knowing the interfacial tension, shear rate and filtration velocities.

2. Theory

In this work, it is assumed that the drops larger than the slotted pore width would deform into a pro-late spheroid. Static force (F_{cx}) comes from the interfacial tension, tries to restore the spherical shape of a drops and oppose the drop deformation. Without shear rate imposed, membrane rejects the drops because of the static force and expressed mathematically as follows [15]:

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

where σ is the interfacial tension between oil/water, R_{sp} is the radius of the drop, α is the angle (34°) at which the slot