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Modeling the Impacts of Liquid Entry Pressure on Membrane Performance during Oil-Water Separation

P. B. Sob

[1]*Doctor of Mechanical Engineering, Department of Mechanical Engineering at the Vaal University of Technology South Africa.*

ORCID: 0000-0002-1796-7694

Abstract

In the current study the flow of liquid entry pressure through a membrane surface was investigated for optimal wettability. In achieving this, the relevant model of liquid entry pressure was developed by taking into the consideration the relevant parameters such as membrane flux recovery process, membrane nanoparticle coating and their impact on surface tension and surface energy driven separability. The tool of stochastic membrane and fluid dynamic was used to model the performance of the membrane during oil-water separation. The following facts was revealed by the derived model equation. It was shown that an increase in liquid entry pressure impacts membrane wettability. The results also revealed the relationship between liquid entry pressure, water flux and flux recovery ratio during oil-water separation. It was also shown that as the liquid entry pressure decreases during oil-water separation, the water flux in the membrane decreases leading to membrane fouling and degradation during oil-water separation. The obtained results also revealed that to increase the membrane flux recovery ratio during oil-water separation, the liquid pressure in the membrane must increases during wettability process if membrane fouling must be minimize during oil-water separation. It was shown that as the membrane change in pressure decreases, the rejection ratio increases to an optimal during wettability process. It was also shown that, to increase membrane performance the change in membrane pressure must increase to an optimal pressure which gave optimal wettability during oil-water separation.

Keywords: Flux, liquid entry pressure, rejection ratio, surface energy, and oil-water separation.

I. INTRODUCTION

Membrane distillation (MD) process is a thermally driven designed membrane surface used in oil-water separation. The designed membrane surfaces the membrane used in oil-water separation must be porous, hydrophobic, and non-wettable. During oil-water separation process, only water must flow through the membrane porous structure. This property is related to the fact that the surface energy of water must be lowered for water to flow through the membrane at the acceptable membrane pore sizes. Subsequently, mass transfer of water through the porous membrane occurs during operation process [1,2]. The rejection of oil and non-volatile components, which can be dissolved salts, and other colloids is not efficient during operation [1,3].

The main driving force in MD is related to the manipulation of membrane surface energy with hydrophobic and hydrophilic nanoparticles. Sometimes the difference in potential of generated chemical and the differences in the transmembrane pressure and transmembrane temperature or by a random decrease of vaporization pressure on the membrane permeate side during operation caused membrane fouling or membrane degradation [3]. Due to the numerous advantages of MD such as its application in lower operating temperatures is one of the main advantage of MD to be acceptable in treatment of temperature-sensitive feed solutions specially in most pharmaceutical and food production companies [4]. During this process there is heat generation which decreases due to change in transmembrane pressure that impacts transmembrane temperature.

To prevent membrane generated heat loss in the membrane during operation, a material with low thermal conductivities is vital from fundamental science and principles. In most MD system there are several key parameters which impacts the generation of heat in the system during operation. These parameters include the type of material used in membrane production, membrane thickness, membrane porosity, the airgap in the membrane pore sizes, the material spatial distribution (type, and thickness) and the polarization of heat in the design system [5]. Most membrane technology which are made from Ceramic membranes are usually designed as asymmetric multilayer material system and the design asymmetric multilayer material consisting of permselective thin film system. This is usually on one or a series networks of porous supports system that usually provide the relevant mechanical stability in the transmembrane and this usually accounts for the minimum transport resistance being reported in the system during operation [6].

During the process of oil-water separation it is vital to consider unique membrane surface modifiers that can enhanced a ceramic membrane surface for stable and efficient wettability. To achieve this the property of the unique membrane are vital parameters to be consider. These parameters are the membrane resistance properties of the substrate during operation. In most previous studies most, research assumed that the properties membrane resistance substrate is negligible which is not the case in a real-life scenario. Most often, it is reported that the properties of membrane resistance substrate are the factor which contribute to membrane effective resistance during operation [7]. This impacts the liquid entry pressure in the membrane which impact the membrane wettability during oil-water separation. It is therefore the main drive that causes most fouling and degradation problem in a membrane system during operation. This directly impacts the mass flow rate of pure water through the membrane surface leading to decline in flux and membrane degradation.

Several research efforts are geared towards increasing membrane flux in MD process by optimizing the membrane parameters such as the distribution of membrane pore size, membrane tortuosity, membrane thickness, membrane pore sizes network, and the membrane porosity and this can impact the flow of liquid entry pressure in the membrane surface during oil-water separation [8–11]. Most implemented studies focus on polymeric membranes surface which are reported to have lower thermal conductivity during operation [5,12]. Ceramic membrane surface is more recommended since ceramic membrane surface has greater thickness which prevent any transfer of heat in the membrane system during operation. In practice, ZrO_2 membrane are reported to have better thermal conductivity when compared to other types of ceramic membranes [13]. The most crucial barriers preventing the widespread industrial process or application of membrane distillation technology used in oil-water separation is membrane wetting pore sizes challenges [3,5,14–18]. The main reasons poor membrane wetting pore sizes are varying liquid entry pressure (LEP) which causes membrane fouling and degradation if not well monitored. The membrane pore sizes network needs optimal characterization for optimal liquid entry pressure (LEP) that will enhance membrane wettability during oil-water separation. Research results revealed that continuous decreased in membrane pore sizes will not improve membrane wettability since smaller membrane pore sizes network led to lower membrane flux and degradation as reported by Sob et al [2020]. Therefore, membrane pore sizes must be characterized for optimal liquid entry pressure during oil-water separation.

Nanoparticles are having the prospect of improving membrane performance if the membrane surface is well modified for optimal performance and this can impact the liquid entry pressure in the membrane. Most membrane modification process with nanoparticles focused on hydrophobization process [20,21] as well as utilizing the application of pretreatment methods [15]. Few researchers used different polymeric membrane such as polyvinylidene fluoride (PVDF), polypropylene (PP), polytetrafluoroethylene (PTFE) due to their low-cost better transport properties in MD [16,18]. However ceramic membrane stands unique due to it thermal and chemical stability when used in MD. Naturally, ceramic membrane is hydrophilic, but they need to be properly hydrophobized for more enhance MD processes during operation [22]. Such modification process must be accomplished optimal membrane characterization of nanoparticles that lower membrane surface energy and change in transmembrane pressure and liquid entry pressure in the membrane during oil-water separation.

For over decades now, researchers have tried to modify ceramic membrane surface for the desalination process. Most of these researches revealed an increase in membrane transport properties through membranes MD immobilization of nanomaterials used on the membrane surface this includes functionalized carbon nanotubes, and modified silica [29,30]. This led to flux enhancement which was achieved by improving the membrane driving force by using the approach of photothermal effect [31] or Joule heating [32] on the hydrophobic produced membrane and this led to an increase in membrane temperature from the feed side, which was subsequently minimalize due to the effect of polarization. Ceramic membrane is also reported to be more stable due to their high biocompatibility during operation [11,33].

It is reported that most research studies in the preparation of more efficient ceramic membranes surface used for desalination process are not efficient due to titania and alumina [8,28]. Similarly, a study on modeling the membrane liquid entry pressure that will improve membrane performance during oil-water separation should be investigated for optimal wettability during oil-water separation.

2.2. METHODOLOGY

For efficient operation of ceramic membrane during oil-water separation, the rejection coefficient of the membrane system during oil-water separation must be minimize. To minimize the rejection coefficient during oil-water separation, it is important to look at the concentration in permeate and feed solution during oil-water. The relationship between these parameters and rejection coefficient can be given as

$$R_{oil/concentration\ mixture} = \left(1 - \frac{C_p}{C_f}\right)100\% \quad [1]$$

where: Cp and Cf is the oil-water mixture concentration in permeate and feed solution, respectively. To model the flow of water through the membrane surface it is important to look at the entry pressure of oil and water mixture (EPOW) in the membrane channel. This is the pressure that separation oil-water mixture by increasing the flux through the ceramic membrane surface and decreases the rejection of oil-water mixture during separation process. This process also depends on nanoparticles coated on the membrane surface which lower membrane surface energy and increases the surface tension due to hydrophobicity. The membrane pore sizes also play a critical role in this process. The critical membrane pore sizes also depend on solution concentration, separation temperature, membrane surface porosity, membrane pore shape, membrane surface roughness and surface smoothness. Therefore, to modify membrane performance that will decrease rejection and increase membrane flux during oil-water separation, these parameters must be taken into consideration at the entry pressure of oil and water mixture (EPOW). In this study, the Purcell model [45] and its modification proposed by Servi et al. [1] was modified for lower rejection of oil-water and high flux of oil-water during separation.

$$LEP = \frac{-2\gamma_L \cos(\theta+\alpha)}{r\left(1+\frac{R}{r}(1-\cos(\theta+\alpha))\right)} \quad [2]$$

$$\sin(\theta+\alpha) = \frac{\sin(\theta+\alpha)}{1+\frac{r}{R}} \quad [3]$$

where R can be related to the radius of the ceramic, r is the size of nanoparticles coated on the membrane surface to lower surface energy and increase membrane flux and α (Eq. (3)) is the angle under the horizontal of the membrane channel. The relationship between membrane pore sizes and nanoparticles sizes coated on the membrane surface is given as

$$r = r_0 - \frac{2\lambda}{\lambda + n} r_p \quad [4]$$

where r_0 is the size of the membrane aperture without any coated nanoparticles on the surface, λ can defined as the actual density of function of nanoparticles being coated on the

membrane channel for hydrophobicity and *n* defined the maximum number of nanoparticle that can be coated on the membrane channel surface to give the desire surface smoothness that lower surface energy and enhanced wettability. There is also a possibility that if the number of particles on the membrane λ increase, the membrane channel cross-sectional area also decreases. Therefore since the sizes of the nanoparticles r_p cannot increase indefinitely as they are limited by the aperture of the channel, it can be proposed that the relationship between the aperture size r, the size of nanoparticles r_p and the number density of particles on the membrane λ can be given by equation [4]. The expression for the maximum number of particles (or grains) to be coated on the membrane surface for proper smoothness was derived from the annulus shown in Fig.1.

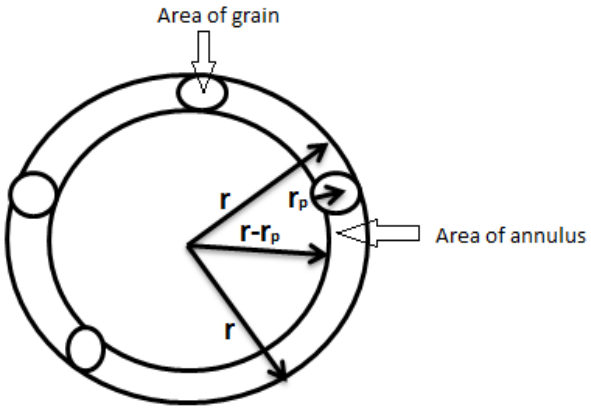


Figure 1 Schematic diagram of membrane channel showing grains, annulus and other parameters used to establish the expression for the maximum number of grains that can be coated in the membrane channel for proper wettability.

The annulus shows nanoparticles that are scattered across it. The surface of the membrane was initially smooth with no coated nanoparticles, which got rougher as coating started and continued. The roughness reached a maximum value and started to decrease (i.e. to become smoother surface) with increasing coating (i.e. with increasing number density of nanoparticles on the surface). As continuous coating took place, it led to complete covering of the nanoparticles over the annulus. The area of the annulus as shown in Fig.1 decreases due to coated nanoparticles on the surface. The area of grain is given as, πr_p^2, that of channel as πr^2 and the remaining internal opening area as $\pi(r - r_p)^2$. Therefore, the area of the annulus is given as $\pi r^2 - \pi(r - r_p)^2$. Hence, the maximum number of grains that can be coated on the pore surface can be given as $n = \frac{Area\ of\ annulus}{Area\ of\ grains} = \frac{\pi r^2 - \pi(r-r_p)^2}{\pi r_p^2}$. Thus, simplifying this expression to equation [5] gives

$$n = \frac{2r\,r_p - r_p^2}{r_p^2} \qquad [5]$$

The area of the membrane channel as derived in equation [5] impacts surface tension and surface energy driven separability given as

$$\delta_{energy} = \frac{FA_1}{2\pi r} = \frac{Fr}{2} \qquad [6]$$

$$\delta_{Tension} = \frac{F}{L} \qquad [7]$$

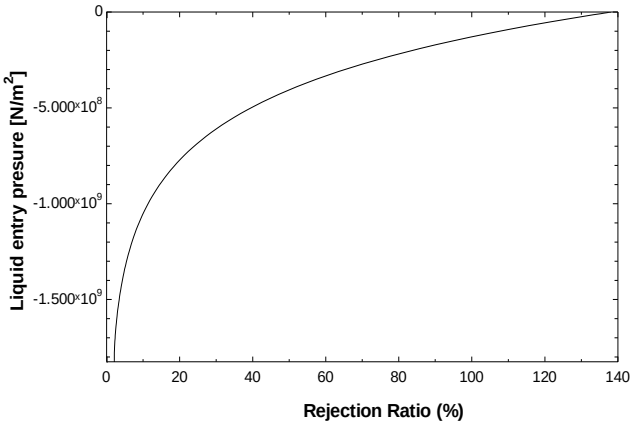
where $A_1 = \pi r^2$ is cross sectional area at inlet, F is the applied force, L is the length of the ceramic membrane channel which can be related to the diameter and radius of the channel given as $r = \frac{D}{2}$ and r is the radius of the channel. For efficient wettability, the resistance in the membrane surface must be minimal and therefore there is an expected change in membrane pressure that can control membrane resistance to increase flux and decrease rejection during oil-water separation. The expression for change in membrane pressure during oil-water separation can be computed by taking compressibility of the flow of oil and water during separation from the point of inlet in the membrane and point of discharge in the membrane given as

$$\Delta P = \frac{\rho_2\rho_1\left(\frac{k-1}{k}\right)\left(\frac{V_1^2}{2} - \frac{V_2^2}{2}\right)}{\rho_1 - \rho_2} \qquad [8]$$

where $k = 1.4$ which is the specific heat, ρ_1 is the density of water at the entrance of the membrane, ρ_2 is the density of water at the exit of the membrane, V_1 is the velocity at the membrane entrance and V_2 is the velocity of water at the membrane exit. The velocities and densities are solved from equation of state on adiabatic process. Equation (4) is the change of pressure waves that influence membrane filtration since it affects fluid changing velocities and changing densities during oil-water separation. By looking at the mass flow rate in the membrane channel at the inlet and exit, the relationship between density, area and velocity at the membrane inlet and exit can be established as $\rho_1 A_1 V_1 = \rho_2 A_2 V_2$. where A_1 is the area of the membrane entrance and A_2 is the exit. Equations (1-8) are solved simultaneously using Engineering Equation Solver software (F-Chart Software, Madison, W153744, USA) and the results are presented and discussed below.

2.3. RESULTS AND DISCUSSION

The proposed models derived in this paper were tested with the following data ρ = 1000 kg/m3, h = 6.626 x 10-34 J.s, μ = 0.000720 m2/s, S1 = 0.3 m, Vvol = 0.12 m3, t2 = 150 sec, t3 = 120 sec, A1 = 0.08 m, A2 = 0.04 m, F = 100 KN. ρ = 1000, S1 = 0.3, V = 200 m/s, t2 = 3 sec, t3 = 1 sec, σ = 0.002, A1 = 0.08 m, A2 =0.0 4 m, F = 100 KN. ρ = 1000 kg/m3, h = 6.626 x 10-34 J.s, μ = 0.000720 m2/s, S1 = 0.3 m, Vvol = 120 litres, t2 = 150 sec, t3 = 120 sec, A1 = 8 cm, A2 = 4 cm, F = 100 KN. ρ = 1000, h = 6.626 x 10-34 μ = 0.000720 N.s/m2, S1 = 0.3 m, $V_{Vol} = 0.12\ m^3$, V = 200 m/s, t2 = 3 sec, t3 = 1 sec, A1 = 0.08 m, A2 = 0.04 m, F = 100 KN. ρ = 1000 kg/m3, S1 = 0.3 m, Vvol = 0.12 m3, t2 = 150 sec, t3 = 120 sec, A1 = 0.08 m, A2 =0.0 4 m, F = 100 KN. The obtained results are presented and discussed.



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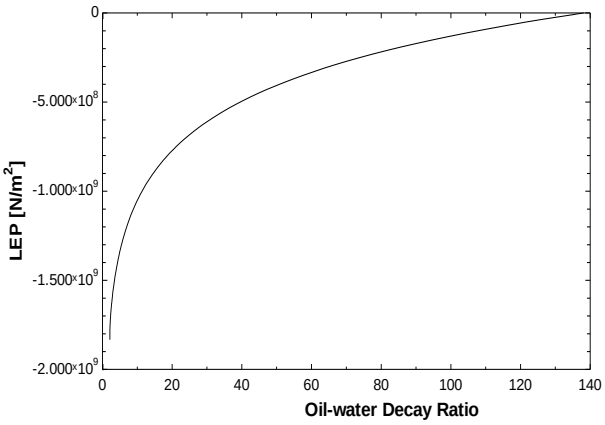
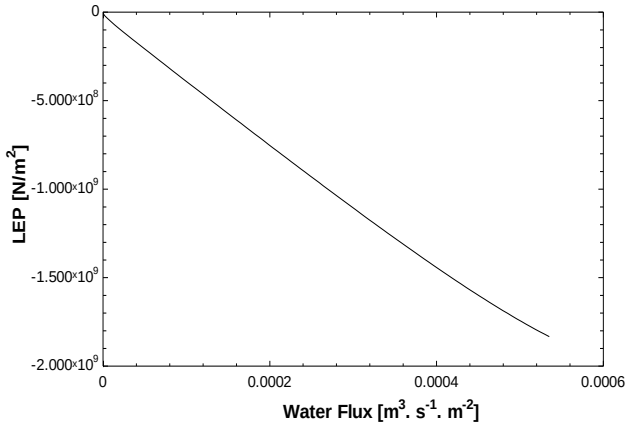


(b)

Figure 2 (a) Liquid entry pressure against rejection ratio (%) and (b) Liquid entry pressure against Oil-water rejection ratio



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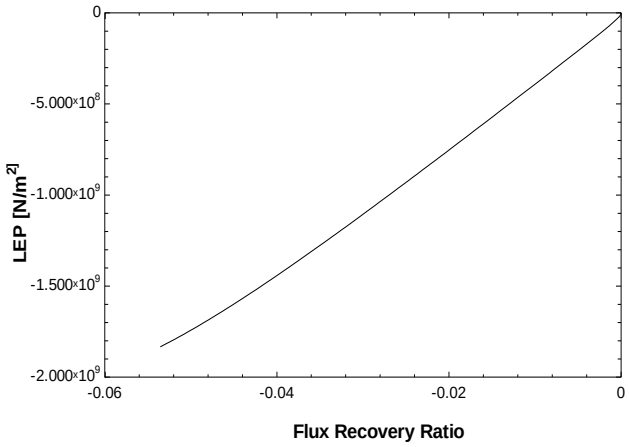


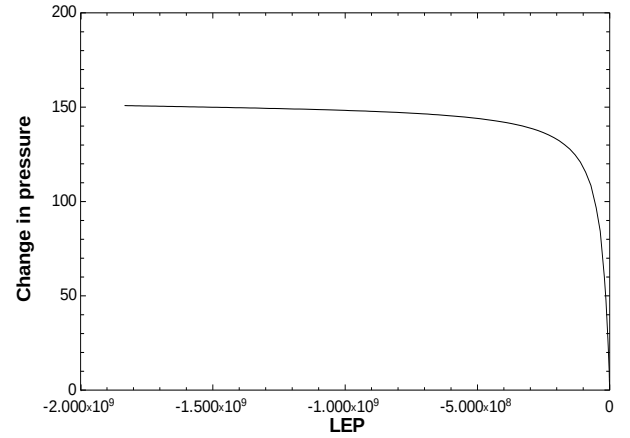
(b)

Figure 3 (a) Liquid entry pressure against water flux and (b) Liquid entry pressure against Flux Recovery Ratio

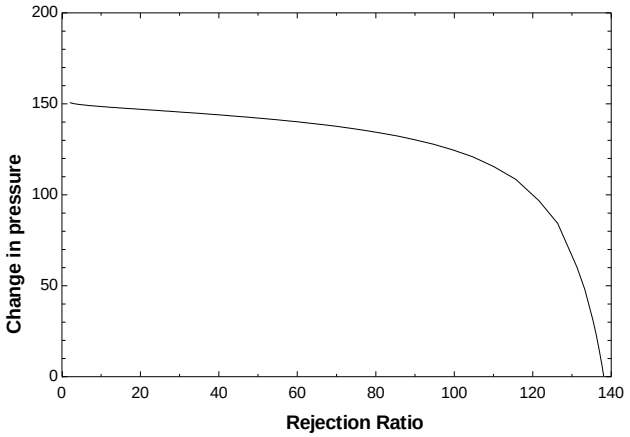
The obtained results revealed in Fig.2 (a-b) shows an increase in liquid entry pressure as the rejection ratio (%) and oil-water decay ratio increases during oil-water separation. The reason for the increase in liquid entry pressure and increase in rejection ratio of oil is can be explained as follows. The designed nanostructured membrane is coated with nanoparticles that lower surface energy to increase membrane wettability during oil-water separation. Since the membrane is hydrophobic, was is not allowed to stay in the membrane channel as water must flow through the membrane channel due to hydrophobic nanoparticles coating that lower surface energy and increase the flow of water through the membrane. If the liquid entry pressure is increase due to an external applied pressure, the force on nanoparticles and viscosity increases. This also impact the reaction force and forces in the membrane channel which increases the flow of water in the membrane channel and at the same time, the rejection ratio of oil in the membrane will increase since the pressure in the membrane has increase. This improve membrane performance as membrane fouling and degradation are minimize. Therefore, this activity impacts the flow of water through the membrane surface as shown in Fig. 3 (a-b).

The results in Fig.3 (a-b) revealed the relationship between liquid entry pressure, water flux and flux recovery ratio during oil-water separation. It is shown that as the liquid entry pressure decreases during oil-water separation, the water flux in the membrane decreases leading to membrane fouling and degradation during oil-water separation as shown in Fig. 3(a). The obtained results also revealed that to increase the membrane flux recovery ratio during oil-water separation, the liquid pressure in the membrane must increases during wettability process if membrane fouling must be minimize during oil-water separation. The reason for the increase in flux recovery ratio due to increase in liquid entry pressure and decrease in water flux due to decrease in liquid entry pressure can be explain as follows. The nanoparticles coated on the membrane surface experiences greater membrane hydrophobicity at optimal liquid entry pressure. Nanoparticles coated on the membrane surface lower membrane surface energy and increase membrane hydrophobic during oil-water separation. When the pressure in the membrane is increase, as the liquid entry pressure increases the forces on nanoparticles increases and the reaction force on the membrane surface increases leading to increase in flow of water through the

membrane channel. Therefore, decrease in liquid entry pressure will decrease membrane flow rate and decreases the membrane flux during oil-water separation as shown in Fig. 3(a-b). The impact of change in membrane pressure and liquid entry pressure is shown in Fig.4 (a-b).



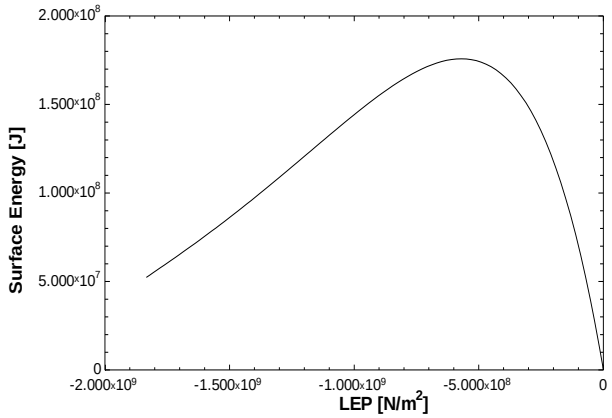
(a)



(b)

Figure 4 (a) Change in pressure against Liquid entry pressure and (b) Change in pressure against Rejection Ratio

The results in Fig.4 (a) revealed a decrease in liquid entry pressure lead to a decrease in change in membrane pressure during oil-water separation. It is also shown from Fig.4(b) that as the membrane change in pressure decreases, the rejection ratio increases during wettability process. During oil-water separation the membrane wettability will be negatively impacted if there is pressure drop in the membrane channel as this decrease's membrane performance during oil-water separation process. To increase membrane performance the change in membrane pressure must increase to an optimal pressure which gave optimal wettability during oil-water separation. Membrane technology and performance are normally analyzed by looking at the surface tension and surface energy and their impacts on wettability as shown in Fig.5 (a-c)



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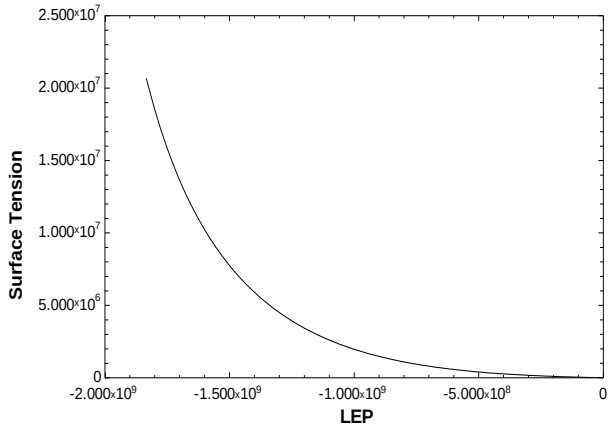

(b)

Figure 5 (a) Surface Energy against Liquid entry pressure and (b) Surface Tension against LEP

The results in Fig.5 (a-b) revealed the relationship between surface energy and liquid entry pressure and it is shown that a decrease in liquid entry pressure led to an increase in surface energy which negatively impacts membrane wettability as shown in Fig. 5(a). The results in Fig.5 (a) revealed that there is an optimal decrease in liquid entry pressure where surface energy start decreasing leading to lower surface energy which increase membrane wettability during oil-water separation. The results in Fig.5 (b) revealed that a decrease in liquid entry pressure lead to an increase in surface tension which increase membrane wettability during oil-water separation. It has been revealed in the current study that membrane liquid entry pressure impacts membrane wettability during oil-water separation.

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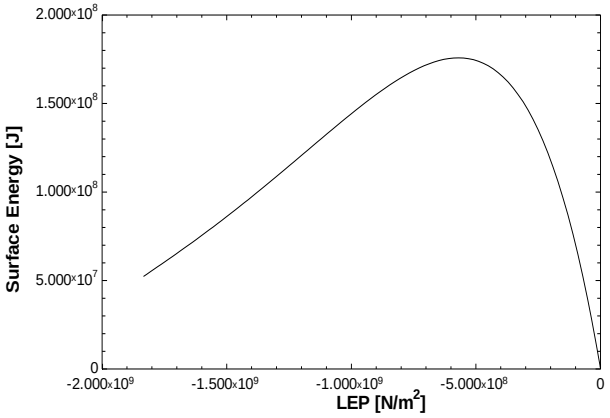
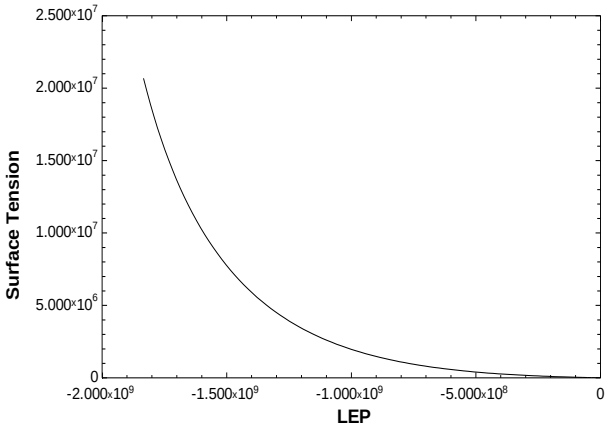
pressure lead to an increase in surface tension which increase membrane wettability during oil-water separation. It has been revealed in the current study that membrane liquid entry pressure impacts membrane wettability during oil-water separation.



(a)



(b)

Figure 5 (a) Surface Energy against Liquid entry pressure and (b) Surface Tension against LEP

IV. CONCLUSION

The aim of the current study was to study the impact of liquid entry pressure on wettability during oil-water separation. To achieve this a model of liquid entry pressure was developed by taking into the consideration membrane flux recovery process, membrane nanoparticle coating, membrane surface tension and surface energy driven separation. The obtained results revealed an increase in liquid entry pressure as the rejection ratio (%) and oil-water decay ratio increases during oil-water separation. The results also revealed the relationship between liquid entry pressure, water flux and flux recovery ratio during oil-water separation. It was shown that as the liquid entry pressure decreases during oil-water separation, the water flux in the membrane decreases leading to membrane fouling and degradation during oil-water separation. The obtained results also revealed that to increase the membrane flux recovery ratio during oil-water separation, the liquid pressure in the membrane must increases during wettability process if membrane fouling must be minimize during oil-water separation. It was shown that as the membrane change in pressure decreases, the rejection ratio increases during wettability process. It was also shown that, to increase membrane performance the change in membrane pressure must increase to an optimal pressure which gave optimal wettability during oil-water separation. It could be concluded that membrane LEP impacts wettability during oil-water separation as revealed in the current study.

V. FUTURE SCOPE

The current study needs experimental validation and the experimentation of the current findings in in progress.

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Conflict of Interest:

No conflict of interest in the study.

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