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Modelling the Effect of Pressure Waves and Velocity of Flow on Membrane Performance During Oil-Water Separation

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Abstract

Several external and internal factors such as pressure waves and velocity of flow affect membrane performance during oil-water separation. In the current study the effect of pressure waves and velocity of flow during wettability process are theoretically investigated and validated by empirical obtained data. The model extension of pressure waves and velocity of flow were developed based on the fundamental principle of fluid flow compressibility in a membrane channel. Change in fluid density and change in membrane pressure and flow velocity were the critical parameters being investigated. This was the first attempt in modelling membrane separability process from compressible flow analysis. The tool of stochastic mechanics and fluid dynamics were used to model membrane change in pressure and flow velocity during oil-water separation. The following facts were revealed theoretically and validated experimentally. It was revealed that, the change in membrane pressure impacts membrane flow velocity, permeability, flow rate and membrane resistance during oil-water separation. It was also revealed that the decrease in membrane resistance and total resistance causes an increase in hydrophobicity. It was also shown that the continuous decrease of membrane resistance and total membrane resistance did not lead to continuous increase in surface energy. The study also revealed critical parameters for surface energy, change in pressure, flow velocity, flux, and membrane resistance during oil-water separation. It was also revealed that the change in pressure and velocity of flow impacted membrane wettability. It was also shown that the change in membrane pressure waves also impacted membrane resistance and velocity during oil-water separation. This was reported to have impacted wettability, leading to an increase in membrane surface energy i.e. increase hydrophobicity during oil-water separation.

Keywords; pressure waves, velocity, membrane performance, oil/water separation, surface energy.

1. INTRODUCTION

Oil-water separation technologies in use today are designed to separation oil-water mixture [1-3]. Conventionally technologies such as gravity separator system and hydro-cyclone separator system are designed with a dispersed phases system during operation [1-4]. This is for continuous phases due to density difference under the force of gravity or centrifugal force being induced by the system during operation at various flow rate [1-5]. In most designed system, as oil-water mixture flows through the centrifugal pump, chokes, valves and membrane surface, the droplets of oil-water mixtures usually became smaller droplets of oil-water mixture by the pressure differential across entire system which affects the density of oil-water molecules [1-4]. Therefore, this is an indication that the flow of oil-water mixture in a membrane technology can be classified as compressible flow and the theory of fluid compressibility can be applicable in membrane modelling and simulation. This has not been extensively studied as most membrane technologies assume that the density of oil-water molecules is constant based on utilisation of Bernoulli's theory in computing change in membrane pressure during oil-water separation. It should be noted that, these small droplets can be stabilized by using surfactants though it is not efficient [1-5]. The surfactants being use forms an encapsulation of hydrophilic or hydrophobic particles on the droplets of oil [1-7]. In the current designed membrane technologies, hydrophilic or hydrophobic particles reduces the interfacial tension leading to coalescence and the separation of smaller droplets become very difficult [1-6].

Research studies revealed the inherent challenges of coalescing emulsified oils when using conventional separation technologies and inefficient separation of finer emulsion droplets of oil-water mixture during oil-water separation [1-6]. This has greatly contributed to the current difficulty in conventional separation deficiencies during oil-water separation [1-6]. The use of nanofiltration and microfiltration systems are becoming better and more efficient in the separation of emulsified oil [1-5]. Membrane separation system namely microfiltration, ultra-filtration, nano-filtration process, and the reverse osmosis (RO) are being used to separate oil-water mixture of different sizes [1]. In most of the current membrane designed, velocity and pressure applied in the oil-water mixture plays a vital role in filtration process [1-5]. In fact, for efficient and stable filtration process, the pressure and velocity of flow in the membrane system must be well monitored during oil-water separation and this must be done by taking into consideration the change fluid densities that causes membrane fouling and degradation. To consider the change in fluid density during oil-water separation membrane pressure change must be model using compressible flow theory. For over decades now, considerable experimental and theoretical data's have been collected without looking at the change in fluid density and it has informed researchers to use low pressure driven membrane pore sizes in microfiltration between 0.1 to 5 μm to improve membrane performance [1-9]. Filtration system like ultrafiltration are designed with a pore size of less than 0.1 μm or ultrafiltration are combined with microfiltration polymeric or ceramic membranes during filtration process [1-

6]. Such designed technologies used low pressure to separate oil-water mixture [1-3]. The efficiency or stability of the system depend on factors such as the choice of the membrane pore size, and not by the difference of density in between the dispersed phase and continuous phase [1-4]. Because of the many unique properties of the membrane which are mostly hydrophobicity due to membrane coating with nanoparticles that lowered surface energy of water and water can easily flow through the membrane [10]. Most research studies have shown that the separation of oil emulsion from water by using ultra/microfiltration are better performed when using ceramic or hydrophilic polymeric membranes [2-5 & 10].

Ceramic membranes are more recommended over polymeric membrane because ceramic membrane have better tolerance to temperature, high oil contents, foulants, and strong cleaning mechanism [1 & 10]. Several research studies have shown that, microfiltration ceramic membranes at pore sizes of 0.2 and 0.8 μm produced better permeate from a feed concentration of approximately 250-1000 ppm of crude oil from a given droplet sizes range of approximately 1-10 μm [1-4]. Studies also revealed that high quality permeate, containing approximately lower than 6 ppm of hydrocarbons in the permeate sample [1-2]. Other researchers have also tested the performance of ceramic in a crossflow microfiltration system to separate oil, grease, and other suspended solids from water [1-4]. It was shown that the permeate quality of dispersed oil and grease was reported to be 5 mg/L and of the suspended solids, it was reported to be less than 1 mg/L [6]. Although this progress has been reported, few applications of this technology in oil-water separation have been implemented successfully specifically in offshore exploration due to changing fluid viscosity that causes membrane fouling and degradation [1-10]. These processes are greatly influenced or control by the operating pressure during filtration and the velocity of flow during filtration [1-8]. It should be noted that, although several pilot studies have been conducted in membrane filtration but with limited success due to the propensity to foul irreversibly with oil and dirt being greatly affected by filtration pressure waves and the filtration velocity [8]. Little or no research has been done on the performance and effect of pressure waves and flow velocity during oil-water [1-15]. There are very few research evidences on membrane pressure waves and velocity of flow during filtration process and also the change in fluid density have not been consider in membrane modeling. Most of the studies focused on membrane pressure, flux, and membrane resistance without looking at the critical change in pressure, resistance, and velocity of flow during oil-water separation in fluids properties with varying density. More so researchers have not model membrane pressure waves, and velocity of fluid flow in varying fluid density on surface energy driven separability. Therefore, the current study is aimed at modelling membrane pressure waves, and membrane velocity in changing fluid density using compressible flow analysis in membrane pressure change and test their impacts on surface energy driven separability.

2. THEORY OF OIL-WATER SEPARATION

The science of flux permeation across a membrane surface is computed by taking into consideration membrane surface area A, being in contact with liquid, the time (t) the experiment was performed and the volume (V) the of permeate collected at a given time interval given as $J = {}^{V}/_{A * t}$. During filtration process, membrane performance is affected by pressure waves, velocity of flow, fluid density which directly affects the flux permeation. Due to change in pressure waves, velocity of flow and fluid density during filtration, varying membrane resistance during filtration process are reported. These activities are clearly defined by the Darcy's Law in membrane filtration [1-15]. The Darcy's law defined membrane parameters such as change in membrane pressure ΔP across a membrane surface, the viscosity permeate fluid during filtration μ, the membrane thickness dx and the membrane permeability K. From the Darcy's Law, V can be related to J which is the flux through the membrane. The flux through the membrane can be given as,

$$J = \frac{K\Delta P}{\mu \Delta x} \quad [1]$$

From the Darcy's Law, the resistance to permeation of a membrane used in oil-water separation is defined as a function of the membrane pore size, velocity of flow and impurities that causes the formation of fouling layer during oil-water separation. Since velocity of flow affect pressure waves in the membrane, the fluid velocity impacts the membrane layers thickness and increase flux. This is seen in the Darcy's Law which states that, flux is directly proportional to the potential pressure drop and inversely proportional to the membrane resistance given by

$$R = \mu R_t \quad [2]$$

From equation (2), it could be observed that, membrane filtration is operating at a varying pressure and velocity which affect viscous flow of fluid in the system and membrane resistance. The flow of viscous fluid in the system during membrane filtration flux is inversely proportional to the membrane total resistance (R_t) during operation. The total membrane resistance during filtration consist of the resistance of the filter media (Rm), which involve the membrane pore blocking resistance (Rp), the membrane resistance to adsorption (Ra), resistance of the internal colloidal fouling mechanism (Rc), the resistance due to membrane formation of a highly concentrated layer due to the membrane, concentration polarization process (Rcp), and finally the resistance due to the formation of the gel layer (Rg), due continuous increase in concentration of particles at the membrane surface during filtration. The total membrane resistance during oil-water separation is given as,

$$R_t = R_m + R_c + R_{cp} + R_g + R_a \quad [3]$$

The membrane resistance during oil-water separation as defined by equation (3) is impacted by membrane pressure waves and speed of oil-water molecules. It is important to study the effect of membrane pressure waves and membrane flow rate during oil-water separation. During oil-water separation, the density of oil and water does not remain constant as water flow through the membrane channel. Practically, the density of water and oil changes from point to point (i.e. from membrane channel inlet to the channel exit) and this affect velocity and the flow pressure in the system. The flow of oil and water in a membrane channel during oil-water separation can be related to a compressible flow because the density of oil and water are not constant. The process cannot be isothermal since temperature is not kept constant and therefore the process can be assumed to be an adiabatic process and therefore membrane pressure waves difference with respect to velocity of flow can be modified from Bernoulli's equation for adiabatic process in compressible flow given as

$$\Delta P = \frac{\rho_2 \rho_1 \left(\frac{k-1}{k}\right)\left(\frac{V_1^2}{2} - \frac{V_2^2}{2}\right)}{\rho_1 - \rho_2} \qquad [4]$$

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 of the membrane area. The area of the membrane channel and change in pressure given by equation (4) can be related to membrane surface energy driven separability used in membrane technology as derived by Sob et al [10] given as

$$\delta_{energy} = \frac{FA_1}{2\pi r} = \frac{Fr}{2} \qquad [5]$$

where $A_1 = \pi r^2$ is cross sectional area at inlet, F is the applied force and r is the radius of the channel which are impacted by nanoparticles that lower surface energy to improve wettability [10]. It must be recalled that the nanoparticles are coated by jet spray on the internal surface of the ceramic membrane channel with some inter-separation distance between them. If the coated nanoparticles are larger in size during jet spray coating, the size of the channel will inversely reduce. 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 rp 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 rp and the number density of particles on the membrane λ can be given by Sob et al.[10] as,

$$r = r_0 - \frac{2\lambda}{\lambda + n} r_p \qquad [6]$$

where r_0 is the size of the aperture without coated nanoparticles, λ the density of nanoparticles coated on the membrane channel and n the maximum number of particles that can be coated on the membrane channel surface to give complete membrane smoothness that leads to lowest surface energy. 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.

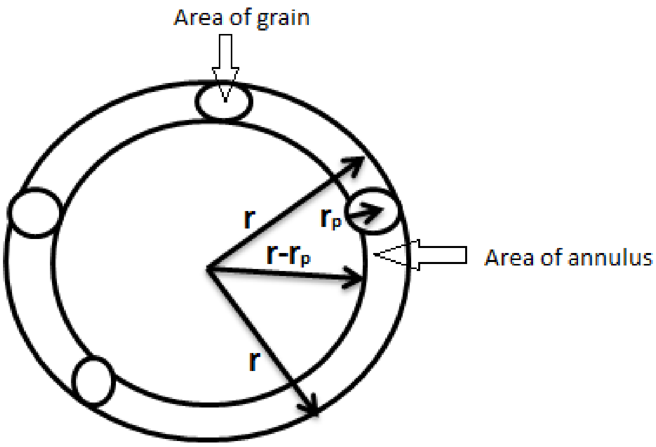

Figure 1. Schematic diagram of membrane channel showing grains, annulus and other parameters used to establish the expression for the maximum number of grains that can be coated in the membrane channel for proper wettability.

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 expression for the maximum number of grains n that should be coated on the membrane channel surface is derived from Fig. 5, by considering the area of the annulus and that of the coated grains. The area of the annulus as shown in Fig. 5 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 $\pi\left(r - r_p\right)^2$. Therefore, the area of the annulus is given as $\pi r^2 - \pi\left(r - r_p\right)^2$. Hence, the maximum number of grains that can be coated on the pore surface can be given as $n = \frac{Area\ of\ annulus}{Area\ of\ grains} = \frac{\pi r^2 - \pi\left(r - r_p\right)^2}{\pi r_p^2}$. Thus, simplifying this expression to equation [7] as defined by Sob et al [10] as

$$n = \frac{2r\,r_p - r_p^2}{r_p^2} \qquad [7]$$

Equations (1-7) are solved simultaneously using Engineering Equation Solver software (F-Chart Software, Madison, W153744, USA) and the results are presented and discussed below.

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,

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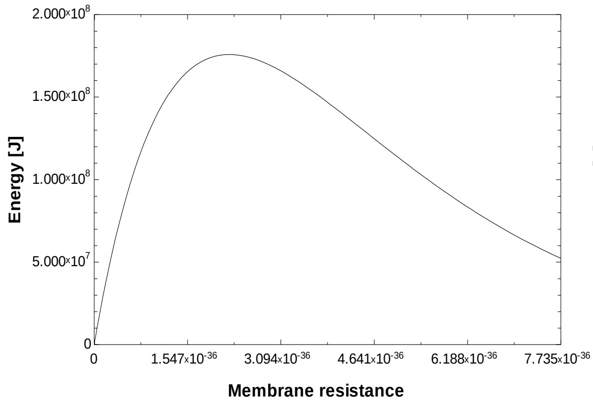
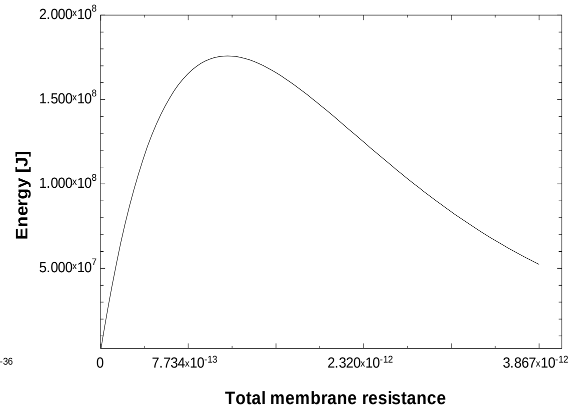
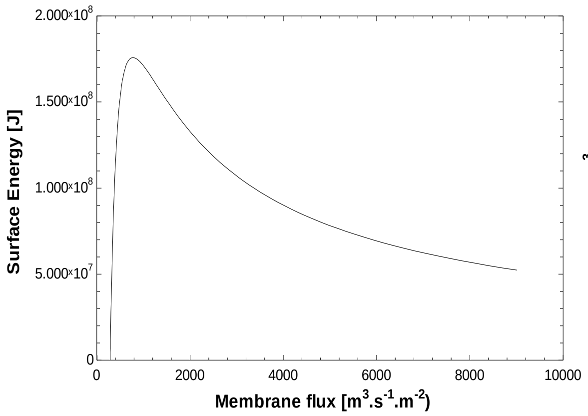
t3 = 120 sec, A1 = 0.08 m, A2 = 0.04 m, F = 100 KN. ρ = 1000, S1 = 0.3, V = 200 m/s, t2 = 3 sec, t3 = 1 sec, σ = 0.002, A1 = 0.08 m, A2 =0.0 4 m, F = 100 KN. ρ = 1000 kg/m3, h = 6.626 x 10-34 J.s, μ = 0.000720 m2/s, S1 = 0.3 m, Vvol = 120 litres, t2 = 150 sec, t3 = 120 sec, A1 = 8 cm, A2 = 4 cm, F = 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.



(a)



(b)



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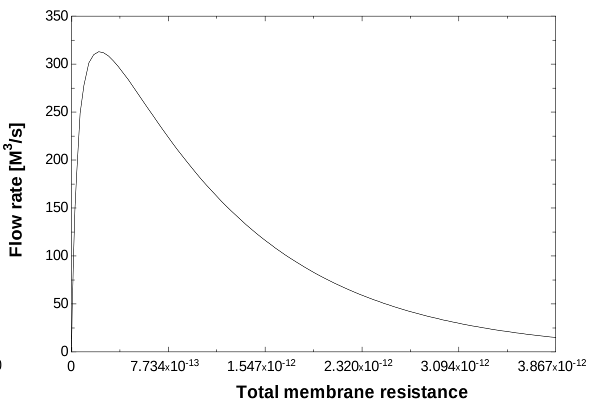

(d)

Figure 2. (a) Energy [J] against membrane resistance (b) Energy [J] against total resistance (c) Energy [J] versus membrane flux (m3.s-1.m-1) (d) flow rate [m3/s] and total membrane resistance

The results in Fig.2 (a-d) reveal the nature of the evolutions of energy (surface energy) on membrane resistance and total membrane resistance during oil-water separation. The result shown in Fig.2 (a-b) reveals that the decrease in membrane resistance and total resistance, led to an increase in membrane energy or surface energy, i.e, increase hydrophobicity. The results also revealed that the continuous decrease of membrane resistance and total membrane resistance did not lead to an increase in energy in the membrane channel during oil-water since the surface became smother or less rough. From Fig. 2 (a-b), it was noted that there was a critical membrane resistance which led to a decrease in surface energy, which impacted membrane flux and membrane wettability or flow rate, leading to hydrophilic surface as shown in Fig. 2 (c-d). The obtained results revealed in this research findings show a smooth transition from high surface energy to low surface energy wettability. There was also a maximum energy during wettability as shown in Fig.2 (a-b) where the membrane surface energy started decreasing, leading to enhancement on flow rate and membrane flux but with poor separability since both oil and water flew through the membrane.

The main reasons for the increasing-to-decreasing surface energy with decreasing membrane resistance were explained to be due to changing aperture roughness and smoothness during coating of ceramic membrane surface used as membrane material. From the study, the best separability during membrane performance where the oil mixture ratio was low was when the energy was higher although the flow rate was still low since the produced membrane was hydrophobic. The results in Fig.2 (c-d) revealed an interesting finding that revealed that for membrane flux to increase during oil-water separation, the surface energy in the membrane must be lowered. Fig.2 (c) revealed that as the surface energy decreases, the membrane flux increases. Therefore, to increase membrane flux, membrane surface energy must be low due to the coated nanoparticles on membrane surface that lowered surface energy to improved wettability. At lower surface energy the flux increases and the flow of pure water through the membrane surface increases leading to increase flow rate as shown in Fig.2 (d). Fig.2 (d) clearly revealed that membrane flow rate will increases steadily when membrane total resistance is continuously decreasing. This impacted the velocity of flow of the separated particles as shown in Fig. 3.

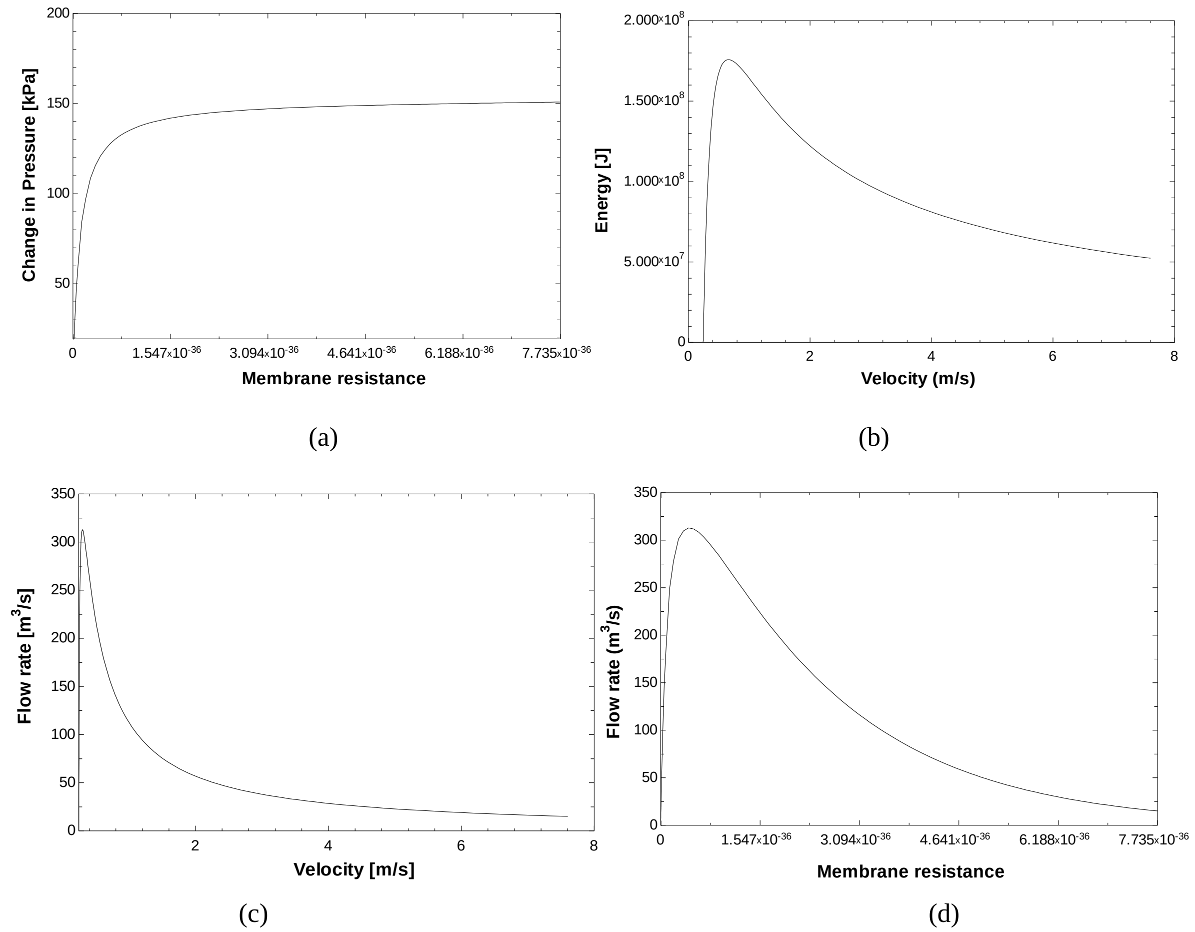

Figure 3. (a) Change in pressure [kPa] against membrane resistance (b) Energy [J] against velocity [m/s] (c) Flow rate [m3/s] versus velocity [m/s] (d) flow rate [m3/s] and total membrane resistance

Figure. 3 (a-d) shows that change in pressure and velocity of flow greatly affect membrane wettability. As seen from Fig.3 (a), change in membrane pressure waves great impacted membrane resistance and velocity during oil-water separation. This affects wettability, leading to an increase in membrane surface energy i.e. increase hydrophobicity during oil-water separation as shown in Fig.3 (c-d). The results revealed in this study shows that, the change in membrane pressure increased to an optima pressure where the change in pressure was steady. It could be seen that through the change in pressure became steady as shown in Fig. 3 (a) membrane resistance was getting steady as the rate of increase in membrane resistance steadily decreases. This change in pressure waves led to change in velocity of flow of the separated particles (oil and water) which affected membrane performance. It also revealed that the continuous decrease in velocity of flow, change in pressure waves and membrane resistance improve surface wettability. This is because the membrane surface energy received the required pressure waves and velocity need for efficient separability to take place. Speed and pressure are critical parameters in wettability. This is because membrane fouling and degradation are minimized by imposing the require pressure waves and velocity during wettability process. Though if the applied pressure and velocity exceed the critical pressure and velocity oil-water mixture will flow through the membrane leading to poor separability. Therefore, the current study is critical since it has revealed the critical pressure and velocity that must be maintain for efficient oil-water separation as shown in Fig. 3 (a-d).

The results shown in Fig.3 (c-d) revealed the impacts of flow rate and membrane resistance due to increase in membrane speed of flow of oil-water molecules during separation and the change in membrane pressure that takes place. The results revealed in the current study show that, it is important to maintain the require velocity of flow and pressure waves in order to improve membrane flow rate during oil-water separation as shown in Fig.3 (c-d). The decreased in membrane velocity of flow lead to decrease in membrane resistance which improve the flow of water through the membrane as revealed in Fig. 3 (b-d). To validate the theoretical obtained results in this study, it is important to compare the obtained modelled and simulated results with other modelled, simulated, and empirical obtained results, as reported by other researchers. The obtained results are compared with that of [11] as shown in Fig. 4 to Fig.6.

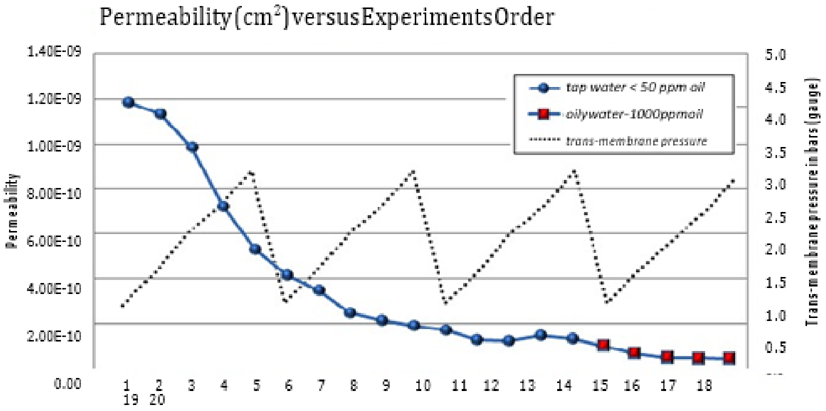

Figure 4: Permeability decline of ceramic membrane of 0.5 μm pore size due to fouling.

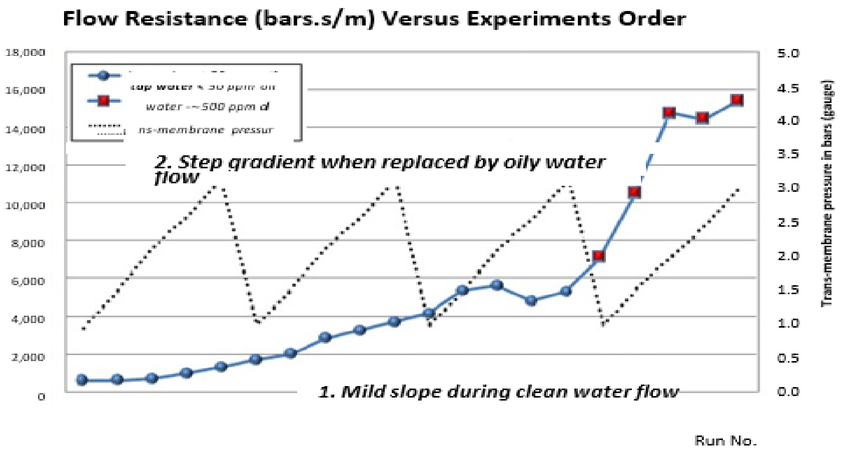

Figure 5: Decrease of flow resistance on the ceramic membrane 0.5 μm was observed when trans-membrane pressure were gradually increased from 1.0 to 3.5 bar(g).

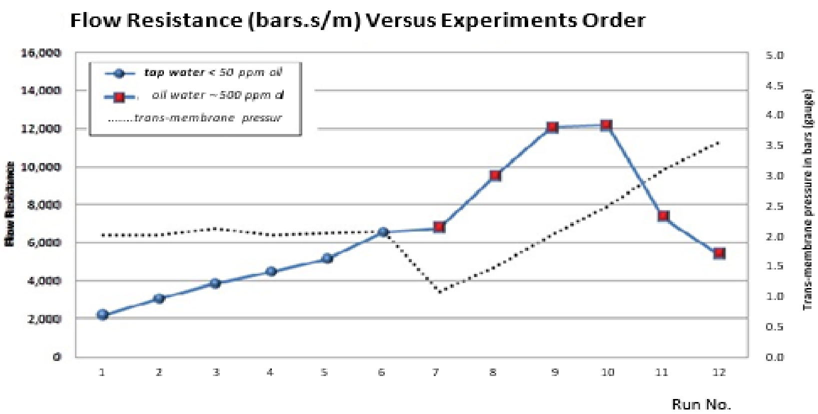

Figure 6: Increase of flow resistance on the 0.5 μm pore size ceramic membrane due to fouling.

Figure 4 to Fig. 6 Image courtesy of [Wai Lam Loh1,2, Thiam Teik Wan1,2*, Vivek Kolladikkal Premanadhan1, Ko Ko Naing1,2, Nguyen Dinh Tam1,2, Valente Hernandez Perez1,2 and Yu Qiao Zhao. 2014:4]

The trend of results revealed by [11] is in line with results revealed in this study. From Fig.4 as different run modes were implemented, the trans-membrane pressure gradually increased from 1 to 3.5 bar(g). This is impacted by the permeability and the rapid decline in permeability which gave high membrane pressure during oil-water separation [11]. As the run increases in experimentation, the membrane performance finally reached a steady balance state between hydrodynamic force and membrane fouling as the expected pressure which constantly sweep away fouling from the membrane surface [11]. From the results revealed by [11], membrane flux linearity depends on trans-membrane pressure drop. This is affected by velocity of flow and membrane resistance as shown in Fig.5 and Fig.6. Membrane flow permeability is impacted by the level of contamination in oil-water mixture and this impacts membrane resistance during wettability as revealed in Fig.5 to Fig.6. In the current research findings membrane optimal change in pressure difference, flux, flow rate, energy and membrane resistance are revealed which other researchers did not reveal. In the current research, the optimal wettability has been reported during oil/water separation. The optimal energy, membrane resistance and pressure difference during oil/water separation has been reported. Therefore, the effect of membrane pressure waves and energy of flow on surface energy driven separability produced more insightful results that were not obtained by other researchers.

4. CONCLUSION AND RECOMMENDATION

The performance of pressure waves and velocity of flow on surface energy driven separability have been investigated. This was achieved by modelling the membrane flux, change in membrane pressure and membrane resistance during oil-water separation. The derived model in this study was tested on surface energy driven separability. The stochastic nature of membrane surface energy driven separability was also taken into consideration. The obtained results revealed the following facts that were validated by comparing with results obtained by other researchers. It was shown that change in membrane pressure effects, flow velocity, permeability, flow rate and membrane resistance are very useful tool for analysis membrane performance during oil-water separation. The obtained results revealed that the decrease in membrane resistance and total resistance causes an increase in hydrophobicity. It was also shown that the continuous decrease of membrane resistance and total membrane resistance did not lead to continuous increase in surface energy. The study also revealed critical parameters for surface energy, change in pressure, velocity, flux, and membrane resistance. It was also revealed that the change in pressure and velocity of flow impacted membrane wettability. It was also shown that the change in membrane pressure waves also impacted membrane resistance and velocity during oil-water separation. This was reported to have impacted wettability, leading to an increase in membrane surface energy i.e. increase hydrophobicity during oil-water separation. The study also revealed the optimal pressure and velocity that impacted wettability process.

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