Estimation of energy consumption during cross-flow membrane filtration of oil/water emulsion

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Abstracts: Pressure driven membrane filtration has been widely adopted for oil and water recovery from oil/water emulsion. The technology offers numerous economic and environmental advantages. However, specific energy consumption remains a critical factor for its economic assessment. The specific energy consumption depends on several factors, among which is the fouling filtration period/time. Therefore, the fouling filtration time indirectly affects the overall economic viability of the system. Herein, the effect of fouling filtration time on the specific energy consumption during cross-flow filtration of 1000 ppm oil/water emulsion was evaluated. During the first 20 min of oil/water emulsion filtration, the energy consumption was found to be 0.0225 KWh/m3. While the filtration was continued to 90 min, the system requires 0.0301 KWh/m3 energy input. The tradeoff between fouling filtration time and energy consumption was found to be just before 30 mins. Suggesting that at 30 mins fouling filtration time, clean water flushing/backwashing would restore significant hydraulic performance and thus, less increase in energy input would be required. At the tradeoff point 0.0254 KWh/m3 energy was required to drive the filtration. This represents up to ~19 % energy saving compared to the straight nonstop 90 min fouling filtration time. The overall results demonstrated that fouling filtration time affects the overall economics of cross-flow membrane filtration.

Keywords: Oil/water emulsion; Pressure driven membrane filtration; fouling filtration time; energy consumption

1. Introduction

A global challenge has been the proper handling of oil/water emulsion produced by oil and gas, pharmaceuticals, and the food industry, etc. [1–3]. Conventional techniques such as dissolved air floatation and many others are inefficient to handle oil/water emulsion properly [4,5]. Pressure-driven membrane processes provide the best economic and eco-friendly option for the treatment of oil/water emulsion [6]. However, pressure-driven membrane systems require energy input to drive their overall separation performances [7–9]. Therefore, an assessment of the energy consumption of the system remains one of the critical factors for its continuous widespread adoption [10]. The energy consumption depends on several factors, among which are the feed property, membrane properties, and operating parameters [10–12]. Those factors directly or indirectly affect the overall membrane performance and thus, affect the energy consumption of the system. Since energy consumption sorely depends on membrane performance [7,13].

Feed property involves the concentration of the model foulant in the feed, which directly affects the membrane performances and therefore affects the energy consumption as well [9]. Membrane properties such as surface wetting property, membrane thickness, and pore size and porosity have a significant effect on the hydraulic and fouling performances of the membrane [14–16]. The operating parameters constitute the operating pressure, filtration set-up, and fouling filtration time [14]. Those factors contributed to the
overall energy consumption of the membrane filtration system. And therefore, should be considered during the economic assessment of the technology [7, 11]. However, many of those are rarely reported in energy consumption assessment such as fouling filtration time [14].

Recently, Li et al. [17] investigated the effect of rotating disk with vanes on energy consumption during linseed oil/water emulsion filtration. The system recorded up to ~140% energy saving against the smooth disk. The smooth disk and disk with vanes exhibited 1070 kWh/m³ and 445 kWh/m³ specific energy consumption, respectively. Substantial reduction in energy input was achieved thanks to the improved hydrodynamic to suppress membrane fouling. Krstić et al. [18] reported energy saving of up to ~40% using the static mixer as turbulence promoter during filtration of cutting oil/water emulsion. Similarly, Vatai et al. [19] also reported tremendous energy saving and attributed it to the hydrodynamic effect induced by the static mixer and the sparged air bubbles.

However, the recently reported energy assessment during oil/water emulsion treatment does not take into consideration the effect of fouling filtration time during the energy assessment [17–19]. Therefore, this manuscript found it necessary to evaluate it effect on the overall energy consumption. This manuscript reported the effect of fouling filtration time on energy consumption during cross-flow filtration of oil/water emulsion. The oil concentration and the trans-membrane pressure (ΔP) of 1000 ppm and 0.2 bar respectively were used throughout the filtration period. The fouling filtration time range 10 to 90 mins, with 10 mins intervals were used, and their respective energy consumptions were evaluated.

2. Material and Methods

2.1 Membrane properties and filtration set-up

The polysulfone ultra-filtration membrane fabricated in the previous study [20] was adopted in this research. The membrane properties are summarized in Table 1. Whereas the cross-flow filtration set-up shown in Figure 1 was used in this study.

| Membrane | Pore size (μm) | Porosity (%) | Thickness (μm) | Contact angle (°) | Rejection (%) |
|-----------|----------------|--------------|----------------|------------------|--------------|
| PSF       | 0.057          | 66.1 ± 0.2   | 234.3±1.3      | 67.1 ± 0.5       | 97.1 ± 2.2   |

The filtration set-up is a simplified one that constituted only the feed pump as the primary source of energy input. The pump outlet pressure was enough to recirculate the retentate to the feed tank, and therefore a recirculation pump was not included in the set-up.
2.2 Oil/water emulsion filtration

The fouling filtration test was conducted according to the previous study [20]. Briefly, the membrane sample was cut and installed into the filtration cell with a 0.0037 m² effective area. The membrane was compacted using clean water at ΔP of 0.2 bar until nearly three same consecutive values were recorded and reported as clean water permeability. The filtration was continued for 90 mins with oil/water emulsion as the feed, and the respective permeabilities were reported every 10 mins. The clean water and oil/water emulsion permeabilities were evaluated using Equation 1. The oil/water emulsion was prepared by mixing crude oil obtained from one of the Petronas oilfields in Malaysia with water that contains 1% surfactant (Sodium Dodecyl Sulfate, Sigma Aldrich, USA). The mixing speed of 3500 rpm was used for a period of 24 h.

\[
L = \frac{V}{At\Delta P}
\]  

(1)

Where \( V \) is the volume of the permeate collected (L), \( t \) is the filtration time (mins.), \( \Delta P \) is the trans-membrane pressure (bar), and \( A \) is the effective membrane area (m²).

2.3 Estimation of energy consumption

In cross-flow filtration set-up, the feed pump is the only energy-consuming component and therefore, is the main component for energy consumption assessment. For the cross-flow filtration set-up, the energy consumption per unit volume of the permeate produced (\( P_p \), KWh/m³) was evaluated using Equation 2.

\[
P_p = \frac{\dot{m}W_p}{V_p}
\]  

(2)

Where \( \dot{m} \) is the mass rate (kg/s) defined by Equation 3, \( W_p \) is the work done by the feed pump (J/kg) defined by Equation 4, and \( V_p \) is the volume of the permeate collected (m³).

\[
\dot{m} = \rho V w L
\]  

(3)

\[
W_p = \frac{\Delta P}{\rho} + \frac{V^2}{2} + F
\]  

(4)

Where \( \rho \) is the density of water (kg/m³), \( V \) is the cross-flow velocity (m/s), \( w \) is the width of the membrane (m), \( L \) is the depth of the flow area (m), \( \Delta P \) is the trans-membrane pressure (Pa), and \( F \) is the laminar flow friction loss (m²/s²).

3. Results and Discussion

3.1 Oil/water emulsion filtration and energy consumption

As shown in Figure 2, the membrane performances declined rapidly. In the first 30 min of the fouling filtration, the performance declined by 27 % while after 90 min, the performance declined by ~39 %. The continuous decline in the performance was due to the continuous increase in hydraulic resistance caused by membrane fouling [21]. Therefore, the declined membrane performance contributed to the increase in the overall power consumption of the system.
Figure 2. Membrane performances and energy consumptions during oil/water filtration.

As the membrane performances decline with time, the energy consumption increases due to the increased hydraulic resistance [7]. To maintain the membrane performance and compensate for the increase in hydraulic resistance, more energy input would be required [12]. In the first 10 min of the fouling filtration, the system requires only 0.0185 KWh/m³ to drive the filtration. However, as the filtration was continued, the system requires up to 0.0301 KWh/m³ to maintain its performance, which is ~63 % more energy input. This is very huge most especially when considering a full-scale operation.

However, the performances and the energy consumption intercepted just before 30 min of operation as shown in Figure 2. The point of interception locates the appropriate time where clean water flushing/backwash would restore significant membrane performance. And therefore, the membrane performances would be prolonged, and less increase in the energy input would be required. 0.0254 KWh/m³ energy was required to drive the filtration at the point of interception. This accounted for ~19 % energy saving compared to the straight nonstop 90 min fouling filtration. The interception point is the tradeoff between filtration time and energy consumption, it gives a guide most especially in auto mode operation to set the backwash setting.

4. Conclusion
This study explores the influence of fouling filtration time on energy consumption during cross-filtration of 1000 ppm oil/water emulsion. Continuous performance decline caused by membrane fouling was observed with an increase in the filtration time. Moreover, the energy consumption increases with an increase in the fouling filtration time. The trade-off point between the fouling filtration time and energy consumption was found to be at 30 min of fouling filtration time. At the trade-off point, the system demonstrated up to ~19 % energy saving compared to the straight nonstop 90 min fouling filtration. Thanks to the clean water flushing that restored significant membrane performances and restricted the hydraulic resistance buildup. And therefore, more energy saving.

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