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Performance of constant-flux immersed UF membrane treating petroleum refinery wastewater

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ABSTRACT

Application of immersed membrane process in treating synthetic and real petroleum refinery wastewater was investigated. The synthetic wastewater investigation was operated at constant flux mode (15, 25, and 40 l/m^2 h) allowing the transmembrane pressure (TMP) to increase with time and oil contents of 20, 50, and 100 mg/l. On the other hand, the real wastewater study was conducted at permeate flux values of 15, 25, and 40 l/m^2 h. The results of the investigation showed that the membrane performance was dramatically affected by wastewater oil content and permeate flux values. The maximum allowable TMP value of 9 ψ was found to be reached frequently with the increase in permeate flux and oil content that resulted in more backwashing and cleaning cycles. As an example, at flux value of 40 l/m^2 h, the membrane module was backwashed 9, 12, and 30 times when oil contents were 20, 50, and 100 mg/l, respectively. Moreover, fouling resistance was found to increase when permeate flux and oil content increased.

Keywords: Constant flux; Transmembrane pressure; Synthetic and real wastewater; Fouling resistance; Membrane cleaning; Permeate quality

1. Introduction

Petroleum industries are the main producers of oil-containing wastewater that results from pumping, desalting, distilling, fractionation, alkylation, and polymerization processes. It is of large volume, and contains suspended and dissolved solids, oil, wax, sulfides, chlorides, mercaptans, phenolic compounds, cresylates, and sometimes large amounts of dissolved iron [1,2]. Refinery wastewater often requires a combination of different treatment methods to remove oil and other contaminants before discharge. A typical system may include sour water striping, gravity separation of oil and water, dissolved air floatation, biological treatment, and clarification [3]. A final polishing step using filtration, activated carbon, or chemical treatment may also be required. Recently, several investigators reported the use of a combination of different conventional and advanced processes in treating oily wastewater such as catalytic oxidation, biological treatment, electro-oxidation, and acidification [4–7]. Advanced technologies were used to remove specific parameters (such as sulfide and phenol) other than oil, while conventional processes depend entirely on operational parameters (such as contact time and chemical addition). It has also been reported that conventional processes are costly [8]. Consequently, and due to increasing stringencies in environmental laws and regulations, applications of innovative technologies such as membranes are encouraged in order to reduce pollution loadings on the environment.

In the published literature, different membrane processes were used to treat oily water by several researchers. Recently, Widiasa et al. [9] investigated the performance of an integrated membrane pilot-scale process when treating oil refinery wastewater. A multimedia filter, an ultrafiltration (UF) unit, a reverse osmosis unit, and a membrane bioreactor (MBR) were used. They reported that in order to reduce the high chemical oxygen demand (COD) value of the MBR effluent, granular-activated carbon adsorption was used. Abbasi et al. [10] used ceramic microfiltration membrane to treat oily wastewater. Effects of transmembrane pressure (TMP), temperature, flow rate, oil concentration, and salt concentration on the performance of the ceramic membrane were investigated. They reported that permeate flux was found to increase with an increase in pressure and temperature, and decrease with an increase in oil and salt concentrations. Effects of operational parameters were the subject of numerous published works [8,11–13]. Generally, researchers reported that operational parameters such as TMP, flow rate, temperature, and oil concentration have dramatic effects on the performance of membranes that is measured in terms of permeate flux rate and quality. Moreover, Rahman and Al-Malack [14,15] investigated the use of MBRs in treating synthetic refinery wastewater. They studied the performance of a MBR, and determined biochemical kinetics at mixed liquor suspended solids (MLSS) values of 3,000 and 5,000 mg/l. Furthermore, Al-Malack [16] treated petroleum refinery wastewater using pilot-scale crossflow and immersed membrane processes. He reported that the immersed membrane process produced stable permeate flux (50 l/m^2 h) throughout the investigation period (800 h), while the crossflow process was found to steadily foul after 600 h. With respect to oil and grease removal, both processes produced permeates that contained less than 1.4 mg/l of oil and grease, which is the detection limit of the analytical method. Recently, immersed membranes have been used to treat different types of oily wastewater such as palm oil mill effluent, produced water, and industrial oily water [17–19]. Investigators used additional processes such as adsorption, electrocoagulation, electroflotation, and surfactants in order to improve the process performance. However, immersed MBRs were reported to produce permeates of high quality. With respect to the use of immersed MBRs, Li et al. [20] investigated the use of anaerobic-/oxic-immersed MBR in treating petroleum refinery effluents. They reported stable and very high removal efficiencies of COD, oil and phenol. Other investigators reported similar results of stable and high removal efficiencies of COD, biochemical oxygen demand, turbidity, phenol, and suspended solids [21].

With respect to membrane cleaning, there is a large selection of available cleaning chemicals. A solution of enzymatic household washing powder is often the first thing to be tried; otherwise, solvents, acid, or alkali solutions could be tried. Bedwell et al. [22] used a standard procedure of backflushing the membrane with pH 1 hydrochloric acid, supplemented when necessary with a prewashing rinse with 1% aqueous sodium hypochlorite solution. Lindau and Jonsson [23] investigated the influence of different types of cleaning agents on a polysulfone UF membrane that was used to treat oily wastewater. More works on fouling control can be cited in Kwon et al. and Kim et al. [24,25].

Based on the above literature review, it could be concluded that applications of immersed membrane processes in treatment of petroleum refinery wastewater require more investigation, particularly, in the area of membrane fouling and cleaning. Moreover, there is a lack of information on the use of immersed membranes as physical processes, not MBRs, in treating petroleum refinery wastewater. Consequently, the main objective of the current investigation is to study the performance of constant flux-immersed membrane when treating synthetic and real petroleum refinery wastewater.

2. Materials and methods

2.1. Synthetic wastewater investigation

In order to optimize the membrane process, experiments were conducted using synthetic oily wastewater, containing different initial levels of crude oil. Effects of flow rate (flux) and oil content on the performance of the membrane process were investigated. Due to the maximum water temperature specified by the manufacturer (40˚C), effect of water temperature on the performance of the process was not investigated. Therefore, all experiments were conducted at room temperature and unadjusted pH values. Table 1 shows the experimental design of the investigation.

Fig. 1 shows a schematic diagram of the bench-scale experimental setup that was used in both investigations. The process, feed, and permeate tanks were made of plexiglass with water capacities of 85, 50, and 25 l, respectively. Dimensions of the feed tank were selected based on the maximum permeate flux to be investigated (40 l/m^2 h). A permeate tank was used to collect the produced permeate that can be used during backwashing cycles, when necessary. The general characteristics of the membrane module are shown in Table 2.

Table 1
Experimental design of laboratory investigation

Experiment number	1	2	3	4	5	6	7	8	9
Period, d	5	5	5	5	5	5	5	5	5
Permeate flux, l/m^2 h	15	25	40	15	25	40	15	25	40
Oil content, mg/l	20	20	20	50	50	50	100	100	100
pH	UA	UA	UA	UA	UA	UA	UA	UA	UA
Temperature,°C	*R*	*R*	*R*	*R*	*R*	*R*	*R*	*R*	*R*

Notes: UA = Unadjusted; *R* = Room temperature.

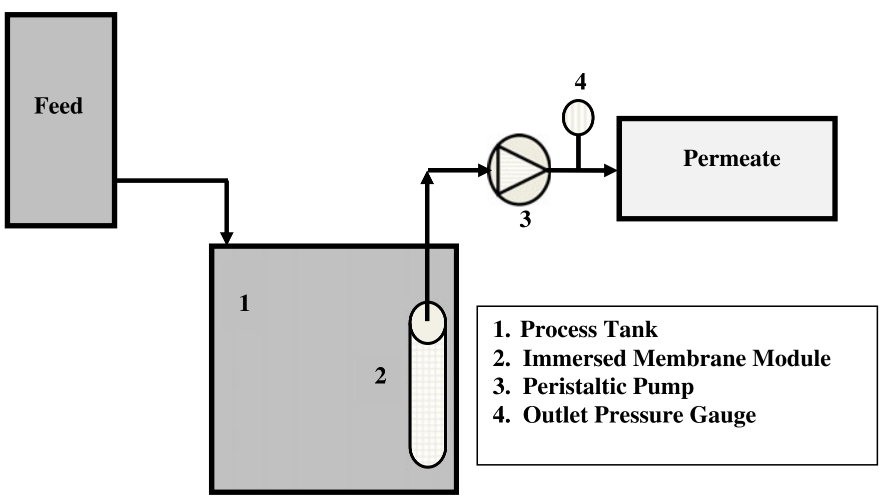

Fig. 1. Schematic diagram of the lab-scale setup.

Table 2
General characteristics of the bench-scale membrane module

Configuration	Hollow fiber
Material	PVDF
Pore size	0.035 μm
Nominal surface area	0.047 m^2
Nominal permeate flow	20 l/m^2 h
Maximum TMP	9 ψ
Typical operating TMP	1–7 ψ
Maximum operating temperature	40°C
Operating pH range	5–10
Maximum transmembrane backwash pressure	8 ψ

The study was conducted using synthetic oily wastewater, containing 20, 50, and 100 mg/l of crude oil. Wastewater samples were collected, at different times, from the process and permeate tanks for chemical analysis and flux measurements. Collected samples were analyzed for total dissolved solids, total suspended solids (TSS), COD, phenol, and oil and grease in accordance with standard methods [26]. Values of permeate flow rate and TMP were recorded. Each experiment was performed for 5 d, after which the membrane was cleaned in accordance with specifications set by the manufacturer and used again.

2.2. *Real wastewater investigation*

The objective of this investigation was to study the feasibility of using immersed membrane processes in treating real refinery wastewater at optimum conditions obtained from the laboratory investigation. Wastewater produced by an American Petroleum Institute (API) separator was used in the current investigation. Since oil content cannot be controlled, its effect on the process performance was not investigated.

Wastewater samples were collected, at different times, from the produced permeate for chemical analysis and flux measurements. Collected samples were analyzed for the same above-mentioned parameters.

2.3. Membrane cleaning

According to the manufacturer specifications, the maximum allowable operating TMP is 9 ψ. Therefore, when that TMP was reached, the membrane was either backwashed or cleaned. Membrane fouling was controlled by air injection, while backwashing of the membrane with the produced permeate was also used, whenever necessary. As specified by the manufacturer, the membrane was cleaned using either basic or acidic solution depending on the type of fouling materials. The membrane module was soaked in a mixture of detergent and caustic soda at pH value of 9.5 for three hours. In case the membrane was not cleaned, the same practice was repeated till satisfactory results were obtained. It is worth to indicate that at least 90% of the membrane permeability should be recovered after cleaning.

3. Results and discussion

3.1. Synthetic wastewater investigation

3.1.1. Effect of permeate flux

It is worth mentioning that permeate flux values were found to slightly fluctuate with time, which could be attributed to the use of a peristaltic pump at low flow rates. However, all efforts were made to maintain permeate flux values close to those under investigation (15, 25, and 40 l/m^2 h). Results of the investigation showed that at oil contents of 20 and 50 mg/l, the process continued to operate throughout the investigation duration (120 h). However, at an oil content of 100 mg/l, Fig. 2 shows that the treatment process had to be terminated after 60 and 8 h when permeate flux values were maintained at 25 and 40 l/m^2 h, respectively. Both investigations were terminated due to frequent backwashing and cleaning cycles were required to maintain the process. It should be noted that at an oil content of 100 mg/l and a permeate flux of 15 l/m^2 h, the investigation continued throughout the designed duration of the experiment.

The effect of permeate flux on TMP at oil contents of 50 and 100 mg/l is depicted in Figs. 3 and 4, respectively. The figures show that as the permeate flux was increased, TMP was also found to increase. This can be attributed to the fact that an increase in permeate flow rate will result in an increase in the volume of the treated wastewater. Consequently, hydraulic resistance of the membrane will increase due to the precipitation of suspended solids (oil) on the surface and within the pores of membrane module. The figures also demonstrate the dramatic effect of oil content on the performance of the treatment process.

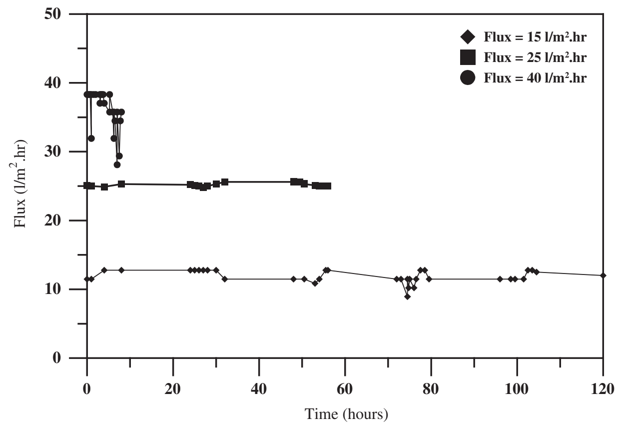

Fig. 2. Permeate flux at oil content of 100 mg/l.

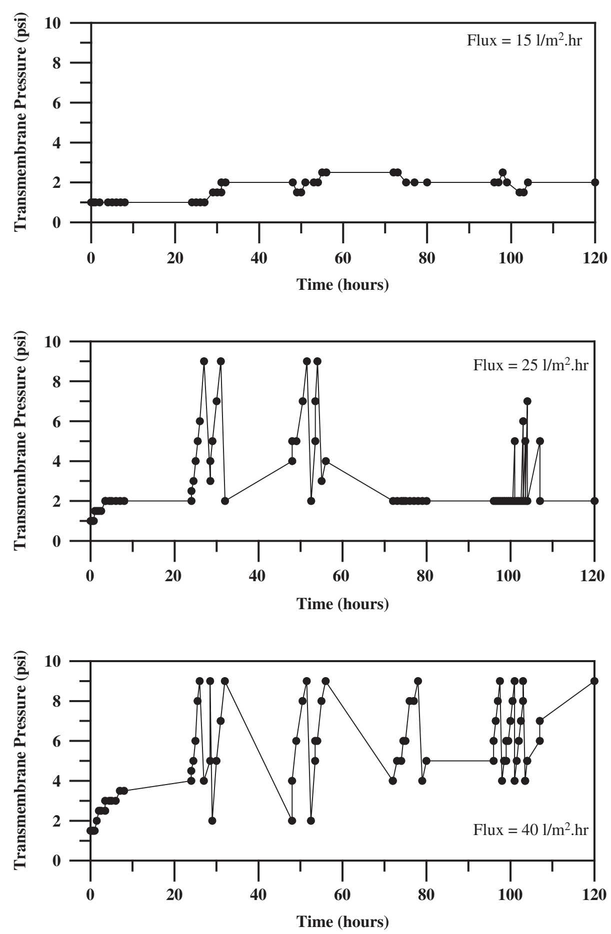

Fig. 3. TMP at oil content of 50 mg/l.

As an example, Fig. 4 clearly shows that the investigation continued for five days when the permeate flux was maintained at 15 l/m^2 h. At this flux rate, the process TMP reached 9 ψ, after two days of operation,

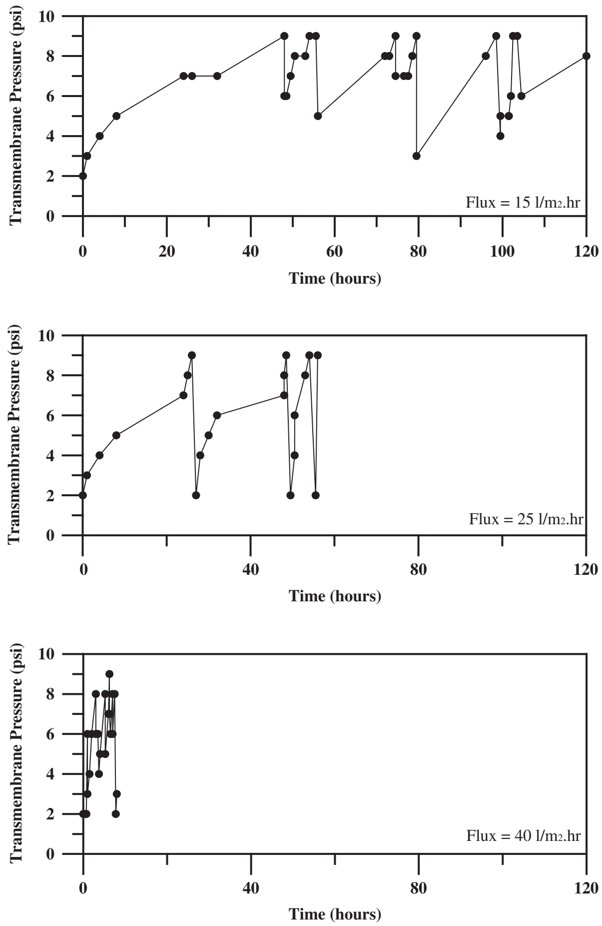

Fig. 4. TMP at oil content of 100 mg/l.

indicating the need for a backwashing cycle. Thereafter, the process needed two backwashing cycles per day. Furthermore, the figure clearly indicates that as the permeate flux was increased, frequencies of reaching a TMP of 9 ψ were also increased. Consequently, the investigation was terminated after 60 and 8 h, when the permeate flux was increased to 25 and 40 l/m^2 h, respectively. Since permeate flow rates were adjusted close to values under investigation, any increase in the membrane hydraulic resistance will definitely result in increasing the membrane TMP.

The relationship between permeate flux and TMP can be also explained by the following Darcy' Law:

$$J = \frac{\Delta P}{\mu R_t} \tag{1}$$

where J = permeate flux; ΔP = TMP; μ = viscosity; R_t = total hydraulic resistance = $R_m + R_p + R_c$; R_m = membrane hydraulic resistance; R_p = hydraulic resistance caused by pore blocking; R_c = hydraulic resistance caused by cake formation.

The law clearly indicates that as the permeate flux increases, TMP will increase. Moreover, several investigators reported similar results on the relationship between flux and TMP [10]. However, Ghaffour et al. [8] who investigated the use of UF in treating petroleum refinery wastewater reported that TMP had relatively little effect on flux, which could be attributed to the increase in hydraulic resistance. Recently, Shanmuganathan et al. [27] investigated the performance of submerged membrane–ion-exchange hybrid system in treating reverse osmosis feed. They reported that the increase of permeate flux values has led to higher TMPs.

3.1.2. Effect of oil content

Three initial oil contents (20, 50, and 100 mg/l) were investigated at different permeate flux values (15, 25, and 40 l/m^2 h). The results showed that as oil contents were increased from 20 to 100 mg/l, TMP values were found to increase accordingly. For example, Fig. 5 shows that at an oil content of 20 mg/l, the TMP exceeded 2 ψ throughout the run. When oil content was increased to 50 mg/l, TMP was found to reach the maximum allowable TMP (9 ψ) more frequently, which resulted in frequent membrane backwashing and cleaning cycles. When oil content was further increased to 100 mg/l, the investigation was terminated after 8 h due to frequent backwashing and cleaning cycles of the membrane. The above results clearly indicate that both of oil content and permeate flux have dramatic effects on TMP that resulted in frequent backwashing and cleaning cycles of the membrane module. Buzatu et al. [28] investigated permeability and clogging in an immersed hollow fiber MBR. They reported that the rate of TMP increase was found to strongly correlate with mass of accumulated solids. Kim et al. [29] investigated new configuration of a MBR for effective control of membrane fouling and nutrients removal in wastewater treatment. They reported that as MLSS concentrations were increased, TMP increase was found to become steep. Similar results on the effect of oil concentration on transmembrane permeate flux were also reported by Abbasi et al. [10] who investigated treatment of oily wastewater using membrane process.

3.2. Real wastewater investigation

3.2.1. Effect of permeate flux

Fig. 6 shows permeate flux values investigated using an API effluent as a feed to the membrane

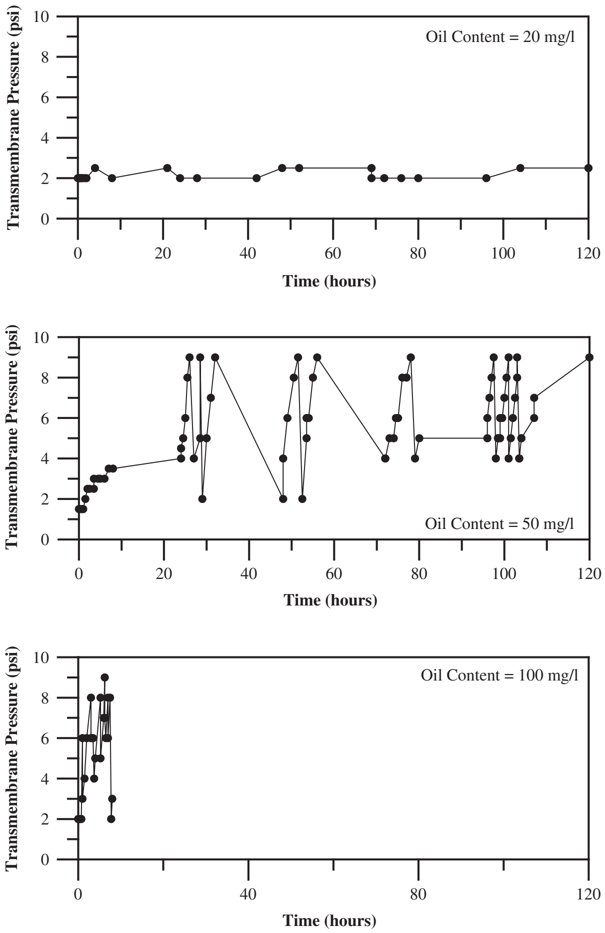

Fig. 5. TMP at permeate flux of 40 l/m^2 h and different oil content values.

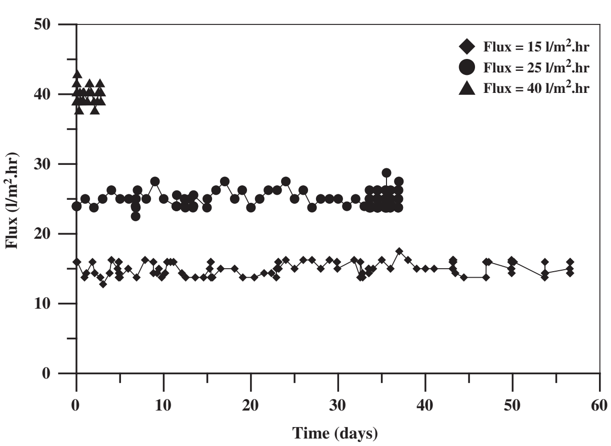

Fig. 6. Permeate flux with respect to time.

process. The figure shows that when a permeate flux of 15 l/m^2 h was investigated, the investigation was carried out for more than 55 d. However, when permeate flux values were raised to 25 and 40 l/m^2 h, the investigation was terminated after about 35 and 3 d, respectively, which can be attributed to the same reasons given above.

The effect of permeate flux rate on TMP is clearly represented in Fig. 7. The figure shows that at a flux of 15 l/m^2 h, TMP values were fluctuating between 1 and 5 ψ for more than 40 d of running time. After that, TMP was found to reach the maximum allowable value (9 ψ) approximately once every 7 d. The results clearly indicate that the immersed membrane process can be operated with minimum backwashing and chemical cleaning cycles when permeate flux values were maintained at 15 l/m^2 h. However, when permeate flux values were increased to 25 l/m^2 h, TMP was found to reach the 9 ψ value more frequently after 5 d of the investigation. Further increase of the permeate flux to 40 l/m^2 h was found to foul the immersed membrane more frequently since the first day of the investigation. The investigation was terminated after less than three days due to frequent backwashing and

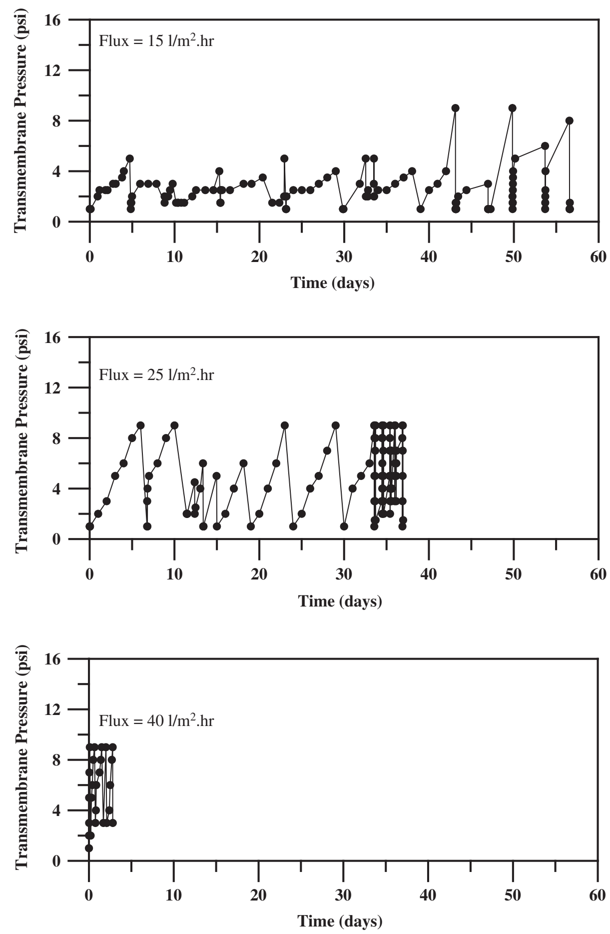

Fig. 7. TMP at different permeate flux values.

cleaning cycles. It can be concluded from the figure that as permeate flow rates were increased, TMP values were found to increase and reach the maximum allowable value recommended by the manufacturer. The increase in TMP can be attributed to the fact that any increase in permeate flow rate will result in an increase in the volume of treated wastewater which will in turn increase the membrane hydraulic resistance due to precipitation of solids on the membrane surface and within its the pores. These results are similar to those obtained when synthetic oily wastewater was used. The results have already been supported by results published in literature.

3.3. Membrane fouling resistance

With respect to the synthetic wastewater investigation, the results clearly revealed that if the process was operated at a permeate flux of 15 l/m^2 h and an oil content of 20 mg/l, the process was not found to foul significantly during the entire experimental period. In this case, the maximum membrane resistance reached a value of about 0.2×10^{-10} (l/m) during the first 10 h of operation. Similarly, when the oil content was increased to 50 mg/l, fouling behavior of the membrane was not found to change significantly. However, when the oil content was further increased to 100 mg/l, membrane resistance jumped to values greater than 0.95×10^{-10} (1/m), which clearly indicates the effect of oil content on the membrane fouling behavior. When the permeate flux was raised to 25 l/m^2 h, the results showed a trend that is almost similar to the above results. Fig. 8 shows the effect of oil content on membrane fouling resistance when the process was operated at permeate flux value of 40 l/m^2 h. The figure shows almost a similar trend, particularly, in the case of 100 mg/l of oil content. In an attempt to represent membrane resistance at different values of permeate flux and oil content, Darcy's Law (Eq. (1)) was rearranged to be become:

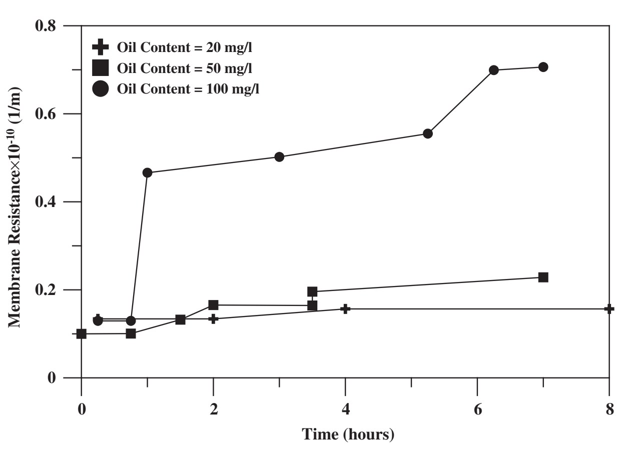

Fig. 8. Membrane resistance vs. time at permeate flux of 40 l/m^2 h.

$$R_t = \frac{\Delta P}{\mu J} \tag{2}$$

or

$$\ln (R_t) = \ln (\Delta P) - \ln (\mu J) \tag{3}$$

Both Eqs. (2) and (3) represent straight lines as long as μ and J are constants. Since the experiments were conducted at constant permeate flux and if μ was assumed to be constant throughout the course of treatment, either Eqs. (2) or (3) can be used to represent the relationship between hydraulic resistance and TMP. Table 3 summarizes the results of plotting fouling resistance vs. TMP at various permeate flux values and oil contents. However, Fig. 9 shows the plots at an oil content of 100 mg/l and different permeate flux values (15, 25, and 40 l/m^2 h). The results clearly indicate the good fit between experimental results and Darcy's law. It is worth mentioning that results presented in Fig. 9 were gathered over periods of 120, 56, and 8 d for flux values of 15, 25, and 40 l/m^2 h, respectively. The investigation results obtained are in agreement with those reported by Sioutopoulos and Karabelas [30] who correlated organic fouling resistances in RO and UF membrane filtration under constant flux and constant pressure. Their results showed an increase in cake resistance with the increase in TMP for both membrane processes. They attributed the increase in resistance to cake compressibility that will increase with increasing the TMP. Moreover, colloidal and bacterial fouling during constant flux microfiltration was investigated by Chellam and

Table 3
Fouling resistance summaries for synthetic wastewater

Oil concentration	Flux (l/m^2 h)	Equations	R^2
20 mg/l	10	$R_t = 0.181 \times \Delta P$	0.99
	20	$R_t = 0.103 \times \Delta P$	0.87
	30	$R_t = 0.059 \times \Delta P$	0.94
50 mg/l	10	$R_t = 0.226 \times \Delta P$	0.99
	20	$R_t = 0.130 \times \Delta P$	0.92
	30	$R_t = 0.064 \times \Delta P$	0.99
100 mg/l	10	$R_t = 0.210 \times \Delta P$	0.99
	20	$R_t = 0.098 \times \Delta P$	0.99
	30	$R_t = 0.072 \times \Delta P$	0.99

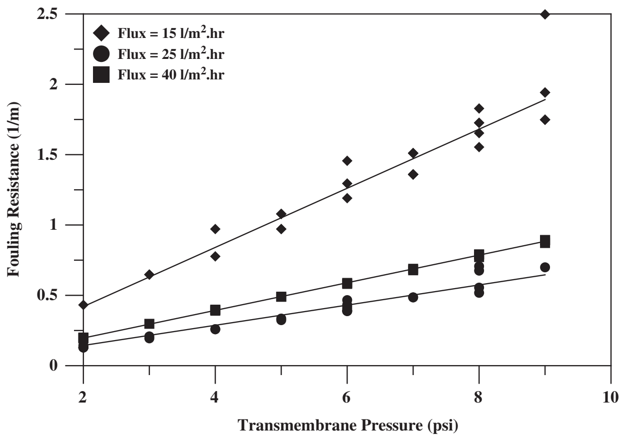

Fig. 9. Fouling resistance vs. TMP at oil content of 100 mg/l.

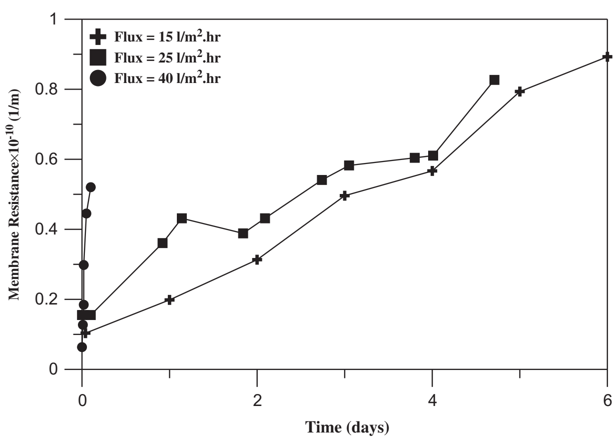

Fig. 10. Membrane resistance vs. time for field study.

Cogan [31]. They reported that fouling resistance due to pore blocking increased over the course of filtration which was attributed to progressive deposition of bacteria within the membrane pores.

In the real wastewater investigation, since oil content was not controlled, only the effect of permeate flux on membrane fouling was investigated. Fig. 10 clearly shows that membrane resistance was increasing with time and with the increase in permeate flux values. When 15 l/m^2 h was used, membrane resistance was found to gradually increase with time till the end of the investigation (more than 55 d). However, when permeate flux was increased to 25 l/m^2 h, membrane fouling was found to be more frequent which resulted in terminating the investigation after 35 d of experimentation. The membrane resistance was insignificantly higher than that obtained at a permeate flux of 15 l/m^2 h. The figure shows that when permeate flux was further increased to 40 l/m^2 h, membrane resistance reached a value that is more than 0.5×10^{-10} (1/m) in the first hours of the experiment, which resulted in terminating the experiment after 3 d. Fig. 11 shows fouling resistance vs. TMP when real petroleum refinery wastewater was used. As in the case of synthetic wastewater, the figure clearly shows the good fit between the law and experimental results ($R^2 = 0.99$). It is to emphasize that at higher flux values (40 l/m^2 h), the maximum fouling resistance was obtained in about 15 h, while in the case of 15 and 25 l/m^2 h, it was obtained in 6 and 5 d, respectively. The results are in agreement with those reported by Parameshwaran et al. [32] who analyzed microfiltration performance with constant flux processing of secondary effluent. The results showed that cake resistance was found to increase with increasing permeate flux, particularly at high TMP values (50 kPa), which was attributed to cake compressibility. Additionally, Miller et al. [33] made a comparison of membrane fouling at constant flux and constant TMP conditions. They reported rapid increase of membrane resistance with the increase of permeate volume/filtration area when permeate flux values were higher than a threshold flux (62 l/m^2 h).

3.4. Membrane backwashing and cleaning

When TMP was found to reach the maximum allowable value (9 ψ), membrane module was backwashed with the collected permeate. Moreover, if the membrane was found to foul frequently, cleaning was performed in accordance with manufacturer's recommendations. Backwashing of the membrane was performed using the collected permeate at a backwashing pressure of 8 ψ for 60 s. Akhondi et al.

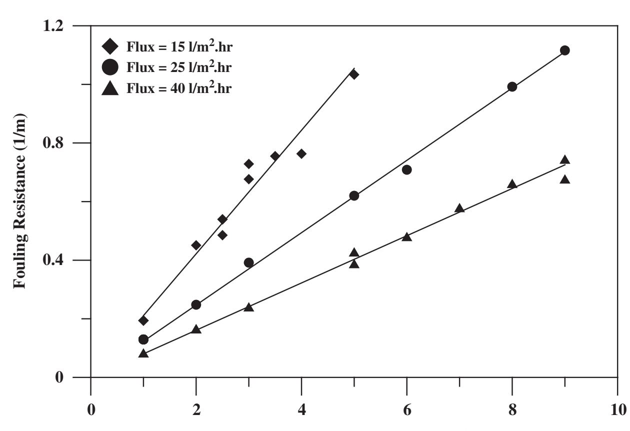

Fig. 11. Fouling resistance vs. TMP for real wastewater.

and McAdam and Judd reported the effectiveness of membrane backwashing in reducing fouling [34,35]. With respect to membrane cleaning, the manufacturer recommended that the membrane should be soaked for three hours in a hypochlorite solution. The recommended cleaning process was not found very effective. Therefore, the manufacturer recommended replacing the hypochlorite solution by a commercial powder detergent (such as DAC, OMO, or TIDE), which was found to be effective. Chemical cleaning of membranes was used by Curko et al. [36] who reported the use of oxalic acid, while Rahman and Al-Malack and Kose et al. [14,18] reported the use of detergents. The average frequency of membrane backwashing and cleaning at different operating conditions of oil content and permeate flux were monitored. Table 4 shows that as permeate flux was increased, backwashing and cleaning frequencies were found to increase. Similarly, an increase in oil content was found to result in increasing the required frequencies of backwashing and cleaning of the immersed membrane. This can be attributed to the same reasons given above. Moreover, higher oil contents were found to produce similar results and, therefore, frequent backwashing or cleaning cycles will be required.

3.5. Permeate quality

Table 5 shows a summary of the general characteristics of the produced permeate at different operational conditions. The table clearly demonstrates that suspended solids were completely removed from the wastewater. Moreover, the concentrations of oil and grease and phenol were always less than the detection limits of the analytical methods used throughout the

Table 4
Backwashing and cleaning cycles at different flux and oil content values

			Permeate flux (l/m^2 h)		
Investigation	Oil content (mg/l)	Backwashing or cleaning cycles	15	25	40
Laboratory	20	Backwashing cycles	5	6	7
		Cleaning cycles	1	1	2
	50	Backwashing cycles	7	9	20
		Cleaning cycles	2	2	3
	100	Backwashing cycles	9	12	30
		Cleaning cycles	3	3	5
Field	25–55	Backwashing cycles	10	15	40
		Cleaning cycles	2	4	10

Table 5
Quality of the permeate at different operational conditions

Operational parameters	TSS (mg/l)	Oil and grease (mg/l)	COD (mg/l)	Phenol (mg/l)
Laboratory investigation				
Oil = 20 mg/lFlux = 15 l/m^2 h	0	<1.0	21	<0.1
Oil = 20 mg/lFlux = 25 l/m^2 h	0	<1.0	10	<0.1
Oil = 20 mg/lFlux = 40 l/m^2 h	0	<1.0	7	<0.1
Oil = 50 mg/lFlux = 15 l/m^2 h	0	<1.0	13	<0.1
Oil = 50 mg/lFlux = 25 l/m^2 h	0	<1.0	18	<0.1
Oil = 50 mg/lFlux = 40 l/m^2 h	0	<1.0	14	<0.1
Oil = 100 mg/lFlux = 15 l/m^2 h	0	<1.0	9	<0.1
Oil = 100 mg/lFlux = 25 l/m^2 h	0	<1.0	7	<0.1
Oil = 100 mg/lFlux = 40 l/m^2 h	0	<1.0	6	<0.1
Field investigation				
Average	0.0	<1.0	70	<1.0
Maximum	0.0	<1.0	191	<1.0
Minimum	0.0	<1.0	6	<1.0

Notes: TSS = total suspended solids; COD = chemical oxygen demand.

investigation (1.4 and 0.1 mg/l, respectively). COD removal efficiency was found to reach 84, 83, and 92% based on the reported average, maximum, and minimum values, respectively. Phenol removal efficiency was found to be 42 and 53% based on average and maximum values, respectively. Several researchers reported high and stable removal efficiencies of oil, COD, suspended solids, turbidity, and phenol when using membrane processes in wastewater treatment [20,37,38].

4. Conclusions

Effects of oil content and permeate flux on the performance of an immersed membrane process in treating petroleum refinery wastewater were investigated using synthetic and real wastewater. Beside the effect of operational parameters, the investigation emphasized on fouling, backwashing, and cleaning of the immersed membrane process. The results clearly indicated that increasing oil content and permeate flux resulted in increasing TMP values, particularly at higher oil contents. The results also showed that as oil content and permeate flux were increased, backwashing and cleaning frequencies of the membrane process were also increased. Fouling resistance was found to increase with the increase of permeate flux and oil content. Moreover, results on fouling resistance were found to have a good fit with Darcy's law. The permeate quality results indicated that removal efficiencies of different contaminants, throughout the course of investigation, were stable regardless of variations in permeate flux and oil content values.

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References

[1] M. Urgun-Demirtas, M.C. Negri, P.S. Gillenwater, A.G.A. Nnanna, J.S. Yu, Meeting world's most stringent Hg criterion: A pilot-study for the treatment of oil refinery wastewater using an ultrafiltration membrane process, J. Environ. Manage. 117 (2013) 65–75.
[2] C. Di Martino, N.I. López, L.J.R. Raiger Iustman, Isolation and characterization of benzene, toluene and xylene degrading *Pseudomonas* sp selected as candidates for bioremediation, Int. Biodeterior. Biodegrad. 67 (2012) 15–20.
[3] B. Diya'uddeen, W. Wan Daud, A.R. Abdul Aziz. Treatment technologies for petroleum refinery effluents: A review, Process Saf. Environ. Prot. 89 (2012) 95–105
[4] C.E. Santo, V.J.P. Vilar, A. Bhatnagar, E. Kumar, C.M.S. Botelho, R.A.R. Boaventura, Sulphide removal from petroleum refinery wastewaters by catalytic oxidation, Desalin. Water Treat. 46 (2012) 256–263.
[5] C.E. Santo, V.J.P. Vilar, A. Bhatnagar, E. Kumar, C.M.S. Botelho, R.A.R. Boaventura, Biological treatment by activated sludge of petroleum refinery wastewaters, Desalin. Water Treat. 51 (2013) 6641–6654.
[6] M.H. Al-Malack, M. Siddiqui, Treatment of synthetic petroleum refinery wastewater in a continuous electro-oxidation process, Desalin. Water Treat. 51 (2013) 6580–6591.
[7] H. Kosal, W. Pattanachot, C. Suksaroj, Treatment of oily wastewater from waste glycerol by acidification and the coalescer process, Desalin. Water Treat. 52 (2014) 2996–3003.
[8] N. Ghaffour, M.W. Naceur, N. Drouiche, H. Mahmoudi, Use of ultrafiltration membranes in the treatment of refinery wastewaters, Desalin. Water Treat. 5 (2009) 159–166.
[9] I.N. Widiasa, A.A. Susanto, H. Susanto, Performance of an integrated membrane pilot plant for wastewater reuse: Case study of oil refinery plant in Indonesia, Desalin. Water Treat. 52 (2014) 7443–7449.
[10] M. Abbasi, A. Salahi, M. Mirfendereski, T. Mohammadi, F. Rekabdar, M. Hemmati, Oily wastewater treatment using mullite ceramic membrane, Desalin. Water Treat. 37 (2012) 21–30.
[11] C.S. Ong, W.J. Lau, P.S. Goh, B.C. Ng, A.F. Ismail, Investigation of submerged membrane photocatalytic reactor (sMPR) operating parameters during oily wastewater treatment process, Desalination 353 (2014) 48–56.
[12] A. Murić, I. Petrinić, M.L. Christensen, Comparison of ceramic and polymeric ultrafiltration membranes for treating wastewater from metalworking industry, Chem. Eng. J. 255 (2014) 403–410.
[13] A. Reyhani, M. Hemmati, Wastewater treatment by ultrafiltration system, considering the effects of operating conditions: Experimental and modeling, Desalin. Water Treat. 52 (2014) 6282–6294.
[14] M.M. Rahman, M.H. Al-Malack, Performance of a crossflow membrane bioreactor (CF–MBR) when treating refinery wastewater, Desalination 191 (2006) 16–26.
[15] M.M. Rahman, M.H. Al-Malack, Biochemical kinetics of crossflow membrane bioreactor processes in the treatment of refinery wastewater, Int. J. Environ. Res. 6 (2012) 285–296.
[16] M.H. Al-Malack, Treatment of petroleum refinery wastewater using crossflow and immersed membrane processes, Desalin. Water Treat. 51 (2013) 6985–6993.
[17] A. Yuniarto, Z.Z. Noor, Z. Ujang, G. Olsson, A. Aris, T. Hadibarata, Bio-fouling reducers for improving the performance of an aerobic submerged membrane bioreactor treating palm oil mill effluent, Desalination 316 (2013) 146–153.
[18] B. Kose, H. Ozgun, M.E. Ersahin, N. Dizge, D.Y. Koseoglu-Imer, B. Atay, R. Kaya, M. Altınbas, S. Sayılı, P. Hoshan, D. Atay, E. Eren, C. Kinaci, I. Koyuncu, Performance evaluation of a submerged membrane bioreactor for the treatment of brackish oil and natural gas field produced water, Desalination 285 (2012) 295–300.

[19] B. Bienati, A. Bottino, G. Capannelli, A. Comite, Characterization and performance of different types of hollow fibre membranes in a laboratory-scale MBR for the treatment of industrial wastewater, Desalination 231 (2008) 133–140.
[20] G.D. Li, N. Li, S.W. Wu, Study on oil refining wastewater treatment by membrane bioreactor with A/O process, in: Proceedings of 1st International Conference on Energy and Environmental Protection, June 23–24 2012, Hohhot, People Republic of China, 2854–2857.
[21] L. Zhidong, Integrated submerged membrane bioreactor anaerobic/aerobic (ISMBR-A/O) for nitrogen and phosphorus removal during oil refinery wastewater treatment, Pet. Sci. Technol. 28 (2010) 286–293.
[22] W.P. Bedwell, S.F. Yates, I.M. Brubaker, Crossflow microfiltration-fouling mechanisms studies, Sep. Sci. Technol. 23 (1988) 531–548.
[23] J. Lindau, A.S. Jönsson, Cleaning of ultrafiltration membranes after treatment of oily waste water, J. Membr. Sci. 87 (1994) 71–78.
[24] O. Kwon, H. Yang, Y. Choi, S. Noh, Fouling control of a submerged membrane module (YEF) by filtration modes, Desalination 234 (2008) 81–88.
[25] J.Y. Kim, I.S. Chang, D.H. Shin, H.H. Park, Membrane fouling control through the change of the depth of a membrane module in a submerged membrane bioreactor for advanced wastewater treatment, Desalination 231 (2008) 35–43.
[26] APHA, AWWA, WEF, Standard Methods for the Examination of Water and Wastewater. 19th ed., APHA, AWWA, WEF, Washington, DC, 1995.
[27] S. Shanmuganathan, T. Nguyen, W.G. Shim, J. Kandasamy, S. Vigneswaran, Performance of submerged membrane—Ion exchange hybrid system with Purolite A502PS in treating reverse osmosis feed, Sep. Purif. Technol. 122 (2014) 24–31.
[28] P. Buzatu, T. Zsirai, P. Aerts, S.J. Judd, Permeability and clogging in an immersed hollow fibre membrane bioreactor, J. Membr. Sci. 421–422 (2012) 342–348.
[29] J.Y. Kim, I.S. Chang, H.H. Park, C.Y. Kim, J.B. Kim, J.H. Oh, New configuration of a membrane bioreactor for effective control of membrane fouling and nutrients removal in wastewater treatment, Desalination 230 (2008) 153–161.
[30] D.C. Sioutopoulos, A.J. Karabelas, Correlation of organic fouling resistances in RO and UF membrane filtration under constant flux and constant pressure, J. Membr. Sci. 407–408 (2012) 34–46.
[31] S. Chellam, N.G. Cogan, Colloidal and bacterial fouling during constant flux microfiltration: Comparison of classical blocking laws with a unified model combining pore blocking and EPS secretion, J. Membr. Sci. 382 (2011) 148–157.
[32] K. Parameshwaran, A.G. Fane, B.D. Cho, K.J. Kim, Analysis of microfiltration performance with constant flux processing of secondary effluent, Water Res. 35 (2001) 4349–4358.
[33] D.J. Miller, S. Kasemset, D.R. Paul, B.D. Freeman, Comparison of membrane fouling at constant flux and constant transmembrane pressure conditions, J. Membr. Sci. 454 (2014) 505–515.
[34] E. Akhondi, F. Wicaksana, W.B. Krantz, A.G. Fane, Influence of dissolved air on the effectiveness of cyclic backwashing in submerged membrane systems, J. Membr. Sci. 456 (2014) 77–84.
[35] E.J. McAdam, S.J. Judd, Optimisation of dead-end filtration conditions for an immersed anoxic membrane bioreactor, J. Membr. Sci. 325 (2008) 940–946.
[36] J. Ćurko, I. Mijatović, M. Matošić, H.K. Jakopović, M.U. Bošnjak, As(V) removal from drinking water by coagulation and filtration through immersed membrane, Desalination 279 (2011) 404–408.
[37] L. Qi, H. Liang, Y. Wang, G.B. Li, Integration of immersed membrane ultrafiltration with the reuse of PAC and alum sludge (RPAS) process for drinking water treatment, Desalination 249 (2009) 440–444.
[38] E. Dialynas, E. Diamadopoulos, Integration of a membrane bioreactor coupled with reverse osmosis for advanced treatment of municipal wastewater, Desalination 238 (2009) 302–311.