Ultrafiltration and Reverse Osmosis Membranes for Treating Wastewater Effluent from Gas Turbine Power Plants using the Statistical Method of Taguchi

Ahmed Faiq Al-Alawy
Assistant Professor
College of Engineering-University of Baghdad
ahmedalalawy@yahoo.com

Mohammed Kamil Al-Ameri
MSC. Chemical Engineer
College of Engineering-University of Baghdad
Mohammed.k.alameri@gmail.com

ABSTRACT

A study on the treatment and reuse of oily wastewater generated from the process of fuel oil treatment of gas turbine power plant was performed. The feasibility of using hollow fiber ultrafiltration (UF) membrane and reverse osmosis (RO) membrane type polyamide thin-film composite in a pilot plant was investigated. Three different variables: pressure (0.5, 1, 1.5 and 2 bars), oil content (10, 20, 30 and 40 ppm), and temperature (15, 20, 30 and 40 ^{o}C) were employed in the UF process while TDS was kept constant at 150 ppm. Four different variables: pressure (5, 6, 7 and 8 bar), oil content (2.5, 5, 7.5 and 10 ppm), total dissolved solids (TDS) (100, 200,300 and 400 ppm), and temperature (15, 20, 30 and 40 ^{o}C) were manipulated with the help of statistical method of Taguchi in the RO process. Analysis of variable (ANOVA) and optimum condition was investigated. The study shows that pressure has the greatest impact on the flux of UF process, while it was temperature for RO process. It was noticed that more than 99% oil removal can be achieved and flux of 580 L/m^2.hr by UF process and that the fouling mechanism of UF process follows the cake/gel layer filtration model. It was concluded that 100% removal of oil content can be achieved along with 99% for the TDS rejection and flux of 76 L/m^2.hr by RO process. The result shows fouling in RO process follows the standard pore blocking model. Process optimization was conducted with confirmation test. It was concluded that the observed values are within ±5% of that the predicted which reflects a strong representative model. The treated wastewater has the characteristics of that used as fresh water and it can be reused to the process to reduce the operation cost.

Keywords: Taguchi, UF, RO, membrane, oily wastewater, reuse

استخدام اغشية الترشيح الفائق و التناضح العكسي في معالجة المياه الملوثة الناتجة من محطات كهرباء العنفات الغازية باستخدام طريقة تاكوشي الاحصائية

أحمد فائق العلوي
استاذ مساعد
كلية الهندسة – جامعة بغداد

محمد كامل العامري
ماجستير هندسة كيمياوية
كلية الهندسة – جامعة بغداد

الخلاصة

تمت دراسة مدى كفاءة اغشية الترشيح الفائق و اغشية التناضح العكسي في معالجة واعادة استخدام المياه الملوثة الناتجة من عمليات معالجة الوقود في محطات كهرباء العنفات الغازية في منظومة ريادية. تم دراسة ثلاث

متغيرات تشغيلية في عمليات الترشيح الفائق, الضغط (0.5 , 1 , 1.5 و 2 بار), درجات الحرارة (15, 20, 30 و 40 درجة مئوية) و تركيز الزيت (10,20,30 و 40 جزء بالمليون) بينما تم تثبيت تركيز الاملاح المذابة عند 150 جزء بالمليون. بينما تمت دراسة اربع متغيرات تشغيلية في عملية الترشيح بالتناضح العكسي, الضغط (5 , 6 , 7 و 8 بار), درجات الحرارة الحرارة (15, 20, 30 و 40 درجة مئوية) ,تركيز الاملاح المذابة (100, 200, 300 و400 جزء بالمليون) و تركيز الزيت (2.5 , 5, 7.5 و 40 جزء بالمليون).تم استخدام طريقة تاكوشي الأحصائية في عملية الترشيح بالتناضح العكسي. خلصت الدراسة الى ان الضغط هو المؤثر الرئيسي على عملية الترشيح الفائق بينما تعتبر الحرارة هي المؤثر الرئيسي في عملية الترشيح بالتناضح العكسي. تشير النتائج الى اكثر من 99% من الزيت يمكن ازالته بعملية الترشيح الفائق مع تدفق يصل الى 580 لتر/ساعة لكل متر مربع و ان عملية الترشيح تنطبق مع ميكانيكية تكوين الطبقة الهلامية. تم الاستنتاج بان عمليات التناضح العكسي قادرة على ازالة جميع الزيوت الملوثة و 99% من الاملاح مع تدفق يصل الى 76 لتر/ساعة لكل متر مربع. لوحظ بان عملية الترشيح في التناضح العكسي تتبع ميكانيكية انسداد المسامات المثالية. تم تخمين الموديل الرياضي و الظروف الامثل باستخدام طريقة تحليل المتغيرات ومن ثم اجراء تجربة اثباتية. لوحظ بان النتائج ضمن ±5% من القيم المتوقعة مما يدل على قوة الموديل الرياضي. تم الاستنتاج بان مواصفات المياه المنتجة مشابهة لمواصفات المياه المستخدمة في عمليات معالجة الوقود لذا يمكن اعادة استخدامها لتقليل الكلفة التشغيلية.

كلمات رئيسية : تاكوشي , الترشيح الفائق, الترشيح بالتناضح العكسي, اغشية, مياه ملوثة بالزيوت, اعادة تدوير.

1. INTRODUCTION

A variety of industrial sources generates large amounts of wastewaters daily. An important fraction of these is the oil in water (O/W) emulsions for which current treatment technologies are often costly and ineffective, **Marchese et al. 2000**. Oily wastewaters are produced by various processes and plants such as oil refineries, petrochemical plants, and metalworking plants. These wastewaters create a major ecological problem throughout the world, **Karakulski et al. 1995**. Another source of oily wastewater is the effluent of gas turbine power plants running on Crude oil at which the main source of oily wastewater is the fuel treatment process, **Kaplan & Majchrzak 1996**.

The high demand for electricity in Iraq encourages the deployment of gas turbine power plants for its offering of fast building and high power production especially in combined cycle system, due to the high fuel consumption and the shortage in gas and refined fuel type, many of these gas turbine nowadays is running on different type of liquid fuel, one of these is the crude oil which needs to be treated and washed to remove sodium salts and avoid the phenomena of corrosion inside the gas turbine which may lead be catastrophic damage and loss in energy, **Eliaz et al. 2002**. This is currently being achieved by washing the fuel with fresh water and separate the two phases by centrifugal equipment with the aid of chemical as demulsifier, such process will also require high capacity water and wastewater treatment facilities, hence, an economic and effective wastewater treatment and water reuse can lower the overall water consumption , on the other hand, the environmental regulations became stricter during the recent years demanding more environmental friendly and economic solutions for wastewater treatment, with the remarkable development in membrane filtration technology these processes now exist as an efficient aid that may have all the features required by the industrial standards and environmental regulations, hence, it is increasingly being applied for treating wastewater from different sources. Conventional methods of wastewater treatment can be categorized into three types, 1) Primary which consists of physical separation steps to remove free oils using gravity and centrifugal separations. 2) Secondary treatment to break oil in water emulsions and to remove the dispersed oil. Common techniques for this step are chemical treatment, flotation, filter coalescence and membrane filtration (microfiltration and ultrafiltration. 3) Tertiary treatment which are a physicochemical process to reduce or remove the levels of dissolved organic and inorganic compounds. These processes utilized evaporation, reverse osmosis and activated carbon adsorption **Yu et al. 2013**.

Membranes have several advantages that made it applicable across a wide range of industries, such advantage like the quality of treated water (permeate) is more uniform regardless of influent variations, no chemicals are needed and the possibility for in-process recycling, **Mondal & Wickramasinghe 2008** . Membrane filtration has been proven effective in treating oily water in different industries including municipal wastewater, **Channabasappa 1977, Nicolaisen 2003**, engine rooms, **Karakulski et al. 1995**, and industrial wastewater **Qin et al. 2004; Salahi, Mohammadi & Rekabdar 2010**, it was also studied in much oily wastewater treatments researches **Orecki & Tomaszewska 2007; Rahimpour et al. 2011**. Microfiltration (MF) and Ultrafiltration (UF) have been introduced as solution for oily wastewater treatment in many studies, **Qin et al. 2004, Cumming et al. 2000, Koltuniewicz et al. 1995, Milić et al. 2014**, however, it was noticed that MF and UF processes fail when it comes to meet the removal of ionic contaminations, i.e., the salt ions. Reverse osmosis processes (RO) has found applications in a wide range of fields, RO has a higher ability to remove total dissolved solids than that of UF and MF processes, therefore, it’s getting more attention as a method of oily wastewater treatment and reuse, **Salahi, Mohammadi, Rekabdar, et al. 2010** . The objective of this work is to investigate the treatment of oily wastewater using UF and RO process for in-process recycling possibilities.

2. DESIGN OF EXPERIMENT AND TAGUCHI METHOD

The conventional technique of studying the effect of multiple factors on the response in an experiment is known as the design of experiments (DOE). This has been in use since Sir Ronald A. Fisher’s worked in agricultural experimentation during the late 1920s. For a full factorial design it is represented as:

$$\text{Number of possible runs} = L^m \qquad (1)$$

Where L = number of levels for each factor and m = number of factors. For the subject experiment of RO process with four variables each with four levels number of runs=4^4 = 256, beside the high cost and time may be involved to run such large number of runs, the interpretation of this number of experimental results may be difficult. For such cases, Dr. Genichi Taguchi from Japan proposed an innovative method utilizing a set of orthogonal arrays (OA), **Roy 2010**. Taguchi approach can be applied with confined knowledge of statistics hence, got high adaptability and gained wide popularity in engineering application, **Ziegel 1997**, and used in many studies related to wastewater treatment, **Milić et al. 2014, Salahi et al. 2015, Madaeni & Koocheki 2006**. The main steps for the experimental design in Taguchi method are (1) determination the objective function, (2) identifying the control factors, (3) selection the orthogonal array (OA), (4) running the experiment, (5) analysis of the data and (6) model confirmation, **Roy 2010**. Taguchi method utilizes a statistical measurement of performance known as signal-to-noise (S/N) ratio, in which signal represents the desirable value while noise represents the undesirable value. There are many different possible S/N ratios, however, two of them are applicable in the present experiments: larger is better (LTB) and small is better (STB), **Ziegel 1997** . In this study, the larger is better (Eq.2) is the flux.

$$\left(\frac{S}{N}\right)_{LTB} = -10\log\left[\frac{1}{n}\sum_{i=1}^{n}\frac{1}{y_i^2}\right] \tag{2}$$

$$\left(\frac{S}{N}\right)_{STB} = -10\log\left[\frac{1}{n}\sum_{i=1}^{n}y_i^2\right] \tag{3}$$

where S is the signal, N is the noise, n is the repetition number of each experiment with the same conditions, y_i is the response of experiment.

3. ANALYSIS OF VARIABLES (ANOVA)

Analysis of variable statistical method (ANOVA) was utilized to study the influence of process parameters and to determine the significant parameters. ANOVA analysis reveals the sum of the square (SS), the degree of freedom (DF), adjusted sum of squares (Adj SS), adjusted mean of square (Adj MS) and the percentage contribution of each parameter. F-value indicates how big the change on the performance that the variation of the parameter makes. P-value determines the significant of each factor on response where the value of less than 0.05 (for a confidence level of 95%) indicates that the factor is significant. The R^2 is a measure of the total variability explained by the model, the adjusted R^2 which is utilized to consider the model significance since it is useful when comparing the model with a different number of terms. ANOVA analysis can help generating different residual plots. Normal probability plot can help to understand if the data are normally distributed and if the variables are influencing the response. Residuals versus fitted values will help to understand if a non-linear relationship exists. The histogram can help to investigate if the data are skewed and/or outliers exist. Residuals versus order of the data can help to understand if there are systematic effects in the data.

Flux and removal efficiency were evaluated as in Eq. 4 (flux calculations) and Eq.5 (removal efficiency):

$$J = \frac{Q_p}{A_m} \tag{4}$$

where, J = flux, (L/hr.m^2), Q_p = Permeate flow rate (L/hr) and A_m = surface area of membrane (m^2).

$$R_C = \frac{C_i - C_p}{C_i} \times 100 \tag{5}$$

where R_C = removal efficiency, C_i, C_p are the initial and permeate concentration of the property respectively,

4. FOULING RESISTANCE

Permeate flux and fouling resistance are key factors for UF and RO process evaluation. Flux shows the amount of permeate rate. Fouling resistance shows the significance of cake/gel layer on the membrane surface and its effect on flux decline. Fouling resistance (R_f) was calculated as follows, **Kazemimoghadam & Mohammadi 2007**:

$$R_f = \frac{TMP}{\mu} \left(\frac{1}{J_{ww}} - \frac{1}{J_{wi}}\right) \tag{6}$$

where: TMP: is the trans membrane pressure, μ is the water viscosity, J_{wi} is the initial water flux, J_{ww} is the water flux after fouling. Membrane physical structure has an important influence on flux. If the pores are larger than the size of oil droplets, these droplets may enter the pores causing irreversible fouling. When the membrane pores are smaller than the droplets in the feed, these particles/oil droplets accumulate over the membrane surface causing the formation of a cake/gel layer. During membrane filtration, the degree of fouling depends upon three main factors: 1) Operation factors 2) feed properties and 3) membrane properties. The operational parameters are such an important factors in deciding the rate of membrane fouling, in particular, increasing pressure enhances formation of the cake/gel layer of higher density and finally leads to complete pore blocking, **Kumar & Roy 2008**. Also, membrane surface chemistry, membrane–solute interactions and solute–solute interactions are the keys to understanding fouling phenomena, **Susanto et al. 2009**.

Most models of membrane fouling correlate the permeate flux with time in terms of a quadratic and/or exponential relationship by assuming pore blockage, adsorption, gel-polarization, and bio-fouling. For a limited operational period, **Salahi, Mohammadi & Rekabdar 2010**. The filtration models are listed in **Table 1**.The standard blocking mechanism occurs when the oil droplets are smaller than that of the membrane pores which leads to an internal pore blocking. The complete blocking mechanism occurs when the oil droplets size is greater than that of the membrane pores. As a result, particles/oil droplets do not enter into the membrane pores and do not permeate through the membrane. The intermediate blocking mechanism occurs when the size of oil droplets is similar to that of membrane pores leading to the membrane pores to be blocked near their entrances on the feed side. The cake formation mechanism occurs when the size of oil droplets is much greater than the pore size; hence they are unable to enter the membrane pores. Factors affecting this type of mechanism are oil droplets deformation, cake compression, and cake/gel layer thickness.

5. EXPERIMENTAL WORK

5.1. Wastewater Feed

Oily wastewater feed used in this experiment was prepared using untreated crude and reverse osmosis permeates water. The mixture was then agitated for one minute using 10,000 rpm homogenizer type Ultra Turrax T46/6 by Janke and Kunkel KG. An emulsifier with hypophilic-lipophilic balance (HLB) value of 7 was added as a 1% as weight percentage to the untreated crude to ensure emulsion stabilization, the emulsifier is a proper quantity mix of Tween 85 and Span 80 both by Thomas Baker, the selection of desired HLB value and the weight percentage was based on some experiments done to evaluate the emulsion stability. It was noticed that with the above-selected conditions the emulsion can still be stable for more than two weeks of observation. TDS value was controlled using lab grade NaCl by Sigma-Aldrich.

5.2. Membrane System

Fig. 1 shows a schematic view of the experiment setup. The system consists of one PVC type hollow fiber UF membrane with molecular weight cutoff of 50K Dalton and surface area of 2 m^2. The UF membrane model is BN-90 and was supplied by Guangzhou Chunke Environmental Technology Co. Ltd. from China.

The system consists also of polyamide thin-film composite RO membrane type HF4-2540 by Axeon USA with an active area of 2.69 m^2. A 100 liter glass tank and NSF BRASS 140 GPH rotary vane pump by Procon USA is driven by Procon 1/2 HP motor where used as feed tank and RO feed pump respectively. A centrifugal pump type PKm 90 by Pedrollo Co. was used as UF feed pump. Pressure gauges are installed at the module inlet and rejection stream, flow meters used to measure permeate and rejection flow rate, throttle valve used at the rejection stream to control the pressure.

5.3. Operation variables

Four control factors were chosen in this work: temperature, pressure, total dissolved solids, and oil concentration, while the time was kept constant at 30 minutes, the factors and their levels are shown in **Table 2**.The choice of the above operation condition was based on real wastewater collected from gas turbine power plant's wastewater treatment facility where its oil contents are 39 ppm, TDS is 150 ppm. The design of Experiment (DOE) with factorial method was utilized in the UF process. While in RO process, Taguchi orthogonal array of 16 runs (L_{16}) was selected as the least number of experiments can be performed to evaluate the effects of above different factors in the RO process.

6. RESULTS AND DISCUSSIONS

6.1. UF Process

It was found that oil removal for UF process exceeds the 96% for all the experimental runs, hence it was not considered as a response and was not included in the optimization process. **Fig. 2** represents the effect of temperature and pressure on oil removal. It was found that higher pressure will lead to lower oil removal; this may be attributed to the fact that the increase in pressure may deform the oil droplet and push it through the pores. The temperature effect on oil removal is increasing at elevated pressure. For example, the increase in temperature from 20 to 30 ^{o}C will decrease the oil removal by 0.2% and 2% at pressure of 0.5 and 2 bars respectively. The negative effect of temperature on the oil removal is due to the pore opening and reduction in oil viscosity.

Fig. 3 represents the Flux at different temperature and oil values. The figure indicates that the oil content decreases the flux linearly. The figure also indicates that the increase in oil concentration will decrease the percentage increase of flux with temperature. For example, the increase in temperature from 20 C to 30 C will increase the flux by 7% when the oil contents are 10 ppm, however, the increase will only be 1.7% when the oil concentration is 30 ppm. This is a result of the cake layer formation which is higher when the oil concentration is high.

Analysis of variables was conducted for the flux data. The results of ANOVA analysis and the model equation are represented in **Table 3**. The adequacy of the model can be predicted from the residual plots of **Fig. 4**. The ANOVA analysis suggest that the greatest contribution to the flux comes from the pressure and that looking at the P-value it can be assumed that all the model parameters are significant. The model presented suggests that it can explain 99.9% of the data.

6.1.1. Fouling Mechanism for UF Process

The flux values from experimental runs of temperature of 30 ^{o}C, pressure of 1 bar and oil concentration of 20 ppm was used to evaluate the fouling mechanism. **Fig. 5** shows the flux decline with time. **Fig. 6** shows different forms of flux (J) with time, the figure indicates that the Cake filtration model is the best fits the experimental runs.

6.1.2. Optimization of UF Process

An optimization process was utilized using Minitab 17 software on UF process results; the aim of this process was to increase both flux and the fouling resistance. The process optimization results are listed in **Table 4**. The results show that the best operation conditions to maximize the flux and the fouling resistance are to operate at a temperature of 40 ^{o}C, the pressure of 2 bars, oil contents of 40 ppm as it is shown in **Table 5**.

6.2. RO Process

Table 6 shows the L16 orthogonal array results, it was found that TDS removal exceeds 98% and oil removal for RO process is 100% for all the experimental runs, hence both were not considered as a response and not included in the optimization process. **Fig. 7** represents the main effect graph for the flux. It shows the influence of individual process parameters on permeate flux at different levels where it can be observed that pressure and temperature have the greatest influence on process parameters due to the steep slope. ANOVA analysis was conducted and the results of analysis are represented in **Table 7**. The analysis indicates that the greatest contribution comes from the temperature and pressure respectively. The P-values indicate that that oil appears to be less significant, while all the other factors are significant. This is may be attributed to the time boundaries for this experiment is lower than that a concentration polarization phenomena to occur and hence lower impact the flux attributed to the oil. The R^2 is a measure of the total variability explained by the model. It can indicate that the presented model can explain 99.9% of the data. The adequacy of the model can be predicted from the residual plots **Fig. 8**. The interpretations of each residual plot in **Fig. 8** are 1) Normal probability plot indicates that the data are normally distributed and the variables are influencing the response. 2) Residuals versus fitted values indicate that the variance is constant and a non-linear relationship exists. 3) Histogram shows that the data are not skewed and no outliers exist. 4) Residuals versus order of the data indicate that there are systematic effects in the data. Hence, it can be concluded that all the values are within the control range, indicating that there is no obvious pattern and unusual structure and also the residual analysis does not indicate any model inadequacy.

6.2.1. Effect of Temperature and Pressure on Flux

Fig. 9 shows a surface and contour plots for the flux as a response to pressure and temperature, both indicate that the temperature has a higher positive impact on flux, this may be related to the increase in membrane permeability and the reduction in water viscosity as the temperature increases. For example, the increase in temperature from 20 ^{o}C to 40 ^{o}C at a pressure of 6 bars will increase the flux zone from 20-30 to 50-60 while the increase of pressure from 6 bars to 8 bars at 20 ^{o}C will only increase the flux from 20-30 zone to that of 30-40 L/m^2.hr.

6.2.2. Effect of Oil and Pressure on Flux

Fig. 10 represents the surface and contour plots for the flux as a response with the pressure and oil concentration, both indicates low effect of oil contamination on flux, however, it became slightly more significant at elevated pressure, this may be related to the formation of cake or gel layer of oil droplet on the membrane surface which leads to the oil droplet compacting on membrane surface and eventually leads to faster membrane fouling.

6.2.3. Effect of Pressure and TDS on Flux

Similar observations to that of oil and pressure interactions were noticed when studying the effect of pressure and TDS on the flux, however, the effect of TDS here seems to be more significant than that of oil contamination; these observations are represented in **Fig. 11**. The figure indicates that the effect of TDS is less at a higher pressure than that of lower pressure. This can be seen as slight increase in slope and expansion in flux zone, for example, it only takes to increase the TDS from 100 to 150 ppm at a pressure of 5 bar to reduce the flux from 30-35 $L/m^2.hr$ zone to that of <30 $L/m^2.hr$, however, at pressure of 8 bars, the TDS value have to be increased to 250 ppm to reduce the flux from the >50 $L/m^2.hr$ zone to that of 45-50 $L/m^2.hr$.

6.2.4. Effect of Oil and TDS on Flux

Fig. 12 represents the surface and contour plots for the flux as a response for oil and TDS. According to these figures the interaction of TDS and oil has a significant effect on the flux value, The plots suggests that oil and TDS have linear effect on flux value, however, TDS shows higher impact on flux decline especially at higher oil concentration values, this may be related to the concentration polarization effect which is more significant at higher feed contaminants. The increase of TDS value from 100 ppm to 400 ppm at oil concentration of 5 ppm will reduce the flux from 42-42.5 zone to that of 40-40.5 one, however, when oil is 10 ppm the reduction will be to <39.5 zones.

6.2.5. Effect of Oil and Temperature

Fig. 13 represents the surface and contour plots for the flux as a response to temperature and oil, the figures suggests that the interaction effect of oil and temperature on flux is very limited, this may be justified that the temperature has the highest contribution to the flux value as it was suggested earlier, however, the inclined zones indicates a slight impact of oil on flux decline.

6.2.6. Effect of TDS and Temperature

Fig. 14 represents the surface and contour plots for flux as a response with the temperature and TDS. The behavior of temperature and TDS interaction is similar to that of temperature and oil in feed contamination interaction; however, we can see from mentioned figures that effect of TDS is higher than that of oil.

6.3. Fouling Mechanism for RO Process

Fig. 15 represents the effect of time on flux decline in RO process at specific conditions of temperature = 25 ^{o}C, pressure = 6 bar, TDS = 200 ppm, and oil contents of 5 ppm. **Fig. 16** indicates that the 1/J^0.5 vs time curve has the closest behavior to the linear regression line. Hence, it can be assumed that the standard block mechanism is the one predominant the flux decline for RO process.

6.4. Optimization and Confirmation Test for RO Process

Response optimization was used to predict the optimum value and operating conditions, the target for optimization was to maximize the flux and the fouling resistance. Equation 6 was used to calculate the fouling resistance, the optimum operation conditions are shown in **Table 8**. Since the optimum conditions were not tested, a confirmation experiment was done with a combination of the optimum levels to compare the results with the expected performance. The predicted outcomes and the observed values after running the above experiment are listed in **Table 8**. The observed vs. predicted results of optimization experiment are shown in **Table 9**. The results indicates that the deviation for the permeate flux is within ±5% error range which may reflect the strength of proposed model. The above results for the process model indicate that the model can be used as a representative for the subject process of treating oily wastewater within the boundary conditions described earlier.

7. CONCLUSIONS

In this study, the treatment of oily wastewater using UF and RO membrane was studied. The factorial method was utilized for the UF process. Taguchi design of experiments (L16) was employed to analyze the different parameters contribution on the simulated oily wastewater treatment using a Hollow fibers UF membrane and polysulfone RO membrane. According to the ANOVA analysis, the most important parameter for maximum permeate flux for UF process was the pressure, while it was the temperature for the RO process. Process optimization was conducted using statistical software. Optimum conditions for UF were pressure = 2 bar, temperature = 40 ^{o}C, and oil =40 ppm, the results showed an oil removal of 96% with a flux of 521.5 L/m^2.hr. The optimum condition for the RO membrane to provide the highest flux with the highest resistance to fouling was found at pressure = 6.5 bars, TDS=250 ppm, oil =7 ppm, and temperature = 27 ^{o}C. The results show that the treated wastewater contains no oil with very low TDS value. The study suggests that the produced permeate is similar to that used in the process, hence the produced water can be reused to the process of fuel oil washing to reduce the operation cost.

REFERENCES

- Channabasappa, K.C., 1977. *Membrane technology for water reuse application*. Desalination, 23(1), pp.495–514.
- Cumming, I.W., Holdich, R.G. & Smith, I.D., 2000. *The rejection of oil by microfiltration of a stabilised kerosene/water emulsion*. Journal of membrane science, 169(1), pp.147–155.
- Eliaz, N., Shemesh, G. & Latanision, R.M., 2002. *Hot corrosion in gas turbine components*. Engineering Failure Analysis, 9(1), pp.31–43.
- Kaplan, H. & Majchrzak, K.E., 1996. *Liquid Fuel Treatment Systems*. GER-3481, General Electric.
- Karakulski, K., Kozlowski, A. & Morawski, A.W., 1995. *Purification of oily wastewater by ultrafiltration*. Separations Technology, 5(4), pp.197–205.
- Kazemimoghadam, M. & Mohammadi, T., 2007. *Chemical cleaning of*

ultrafiltration membranes in the milk industry. Desalination, 204(1), pp.213–218.

- Kim, J., Chinen, A. & Ohya, H., 1997. *Membrane microfiltration of oily water. In Macromolecular Symposia*. Wiley Online Library, pp. 413–418.
- Koltuniewicz, A.B., Field, R.W. & Arnot, T.C., 1995. *Cross-flow and dead-end microfiltration of oily-water emulsion. Part I: Experimental study and analysis of flux decline*. Journal of membrane science, 102, pp.193–207.
- Kumar, S.M. & Roy, S., 2008. *Recovery of water from sewage effluents using alumina ceramic microfiltration membranes*. Separation Science and Technology, 43(5), pp.1034–1064.
- Madaeni, S.S. & Koocheki, S., 2006. *Application of taguchi method in the optimization of wastewater treatment using spiral-wound reverse osmosis element*. Chemical Engineering Journal, 119(1), pp.37–44.
- Marchese, J. et al., 2000. *Pilot-scale ultrafiltration of an emulsified oil wastewater*. Environmental science & technology, 34(14), pp.2990–2996.
- Milić, J.K. et al., 2014. *Ultrafiltration of oil-in-water emulsion by using ceramic membrane: Taguchi experimental design approach*. Central European Journal of Chemistry, 12(2), pp.242–249.
- Mondal, S. & Wickramasinghe, S.R., 2008. *Produced water treatment by nanofiltration and reverse osmosis membranes*. Journal of membrane science, 322(1), pp.162–170.
- Nicolaisen, B., 2003. *Developments in membrane technology for water treatment*. Desalination, 153(1), pp.355–360.
- Orecki, A. & Tomaszewska, M., 2007. *The oily wastewater treatment using the nanofiltration process*. Polish Journal of Chemical Technology, 9(4), pp.40–42.
- Qin, J.-J. et al., 2004. *Dead-end ultrafiltration for pretreatment of RO in reclamation of municipal wastewater effluent*. Journal of membrane science, 243(1), pp.107–113.
- Rahimpour, A. et al., 2011. *Treatment of oily wastewater produced by washing of gasoline reserving tanks using self-made and commercial nanofiltration membranes*. Desalination, 265(1), pp.190–198.
- Roy, R.K., 2010. *A primer on the Taguchi method*, Society of Manufacturing Engineers.
- Salahi, A. et al., 2015. *Experimental investigation and modeling of industrial oily wastewater treatment using modified polyethersulfone ultrafiltration hollow fiber membranes*. Korean Journal of Chemical Engineering, pp.1–18.
- Salahi, A., Mohammadi, T., Rekabdar, F., et al., 2010. *Reverse osmosis of refinery oily wastewater effluents*. Iranian Journal of Environmental Health Science & Engineering, 7(5), p.413.
- Salahi, A., Mohammadi, T. & Rekabdar, F., 2010. *Reverse osmosis of refinery oily wastewater effluents*. Iranian Journal of Environmental Health Science & Engineering, 7(5), pp.413–422.
- Susanto, H., Feng, Y. & Ulbricht, M., 2009. *Fouling behavior of aqueous solutions of polyphenolic compounds during ultrafiltration*. Journal of food engineering, 91(2), pp.333–340.
- Vela, M.C.V. et al., 2008. *Analysis of membrane pore blocking models applied to the ultrafiltration of PEG*. Separation and Purification Technology, 62(3), pp.489–498.

- Yu, L., Han, M. & He, F., 2013. *A review of treating oily wastewater*. Arabian Journal of Chemistry.
- Ziegel, E.R., 1997. *Taguchi Techniques for Quality Engineering*. Technometrics, 39(1), pp.109–110.

NOMENCLATURE

Symbol	Definition	Units
A_m	Membrane surface area	m^2
ANOVA	Analysis of variance	
C_f	Feed concentration	g/l
C_p	Permeate concentration	g/l
C_m	Concentration at the membrane surface	g/l
ΔC	Difference in salt concentration across membrane	g/l
C	Concentration of solute	g/l
DOF	Degree of freedom	
HLB	Hypophilic-Lipophilic balance value	
J	Flux (wastewater feed)	$l/m^2.hr$
J_S	Flux (Oil free feed)	$l/m^2.hr$
J_0	Flux (distilled water feed)	$l/m^2.hr$
MS	Mean of squares	
t	Time	min
V	Volume	M3
v	Velocity	
P	Pressure	bar
Rf	Resistances of the foulants	1/m
R^2	Percentage of variation in the response	
SS	Sum of square	
SS_T	Total Sum of square	
T	Temperature	^oC
TDS	Total dissolved solids	ppm
TMP	Trans-Membrane Pressure	bar
TSS	Total Suspended solids	ppm
TFC	Thin film composite membrane	
S/N	Signal to noise ratio	

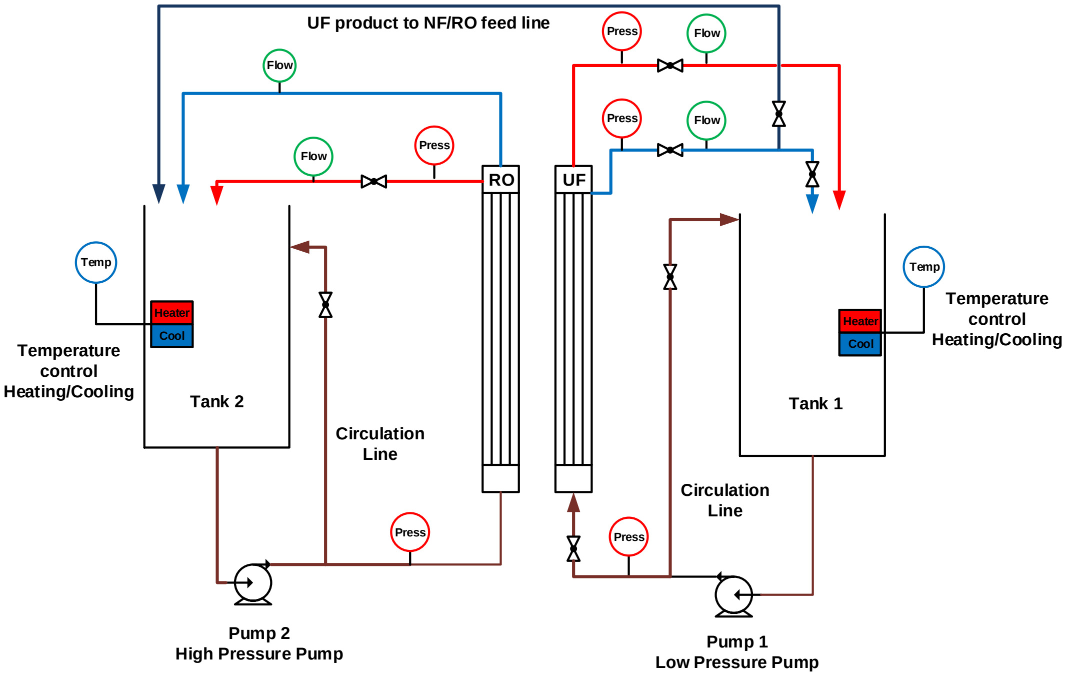

Figure 1. Schematic View of Membrane System.

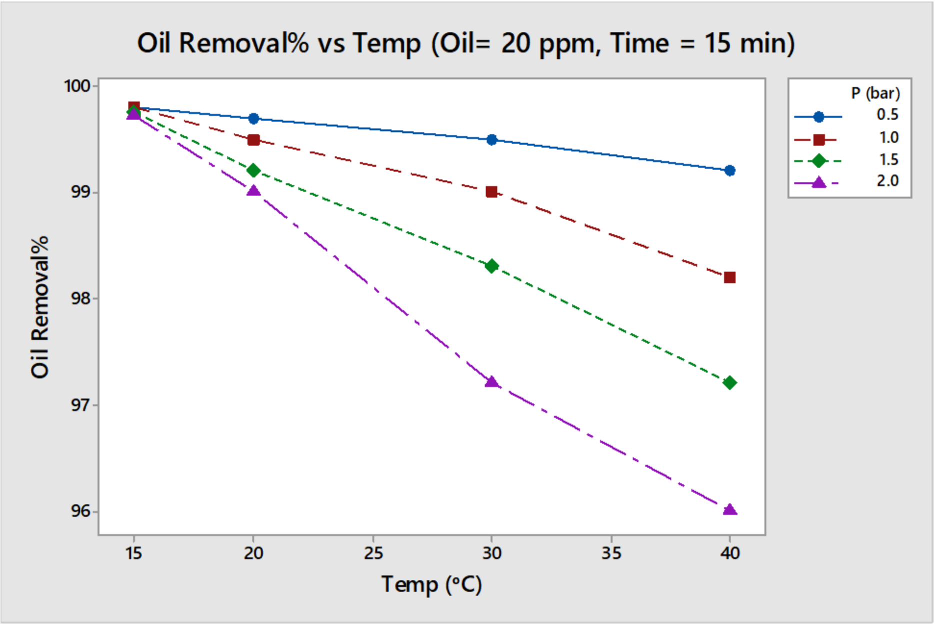

Figure 2. Effect of Temperature and oure on Oil Removal.

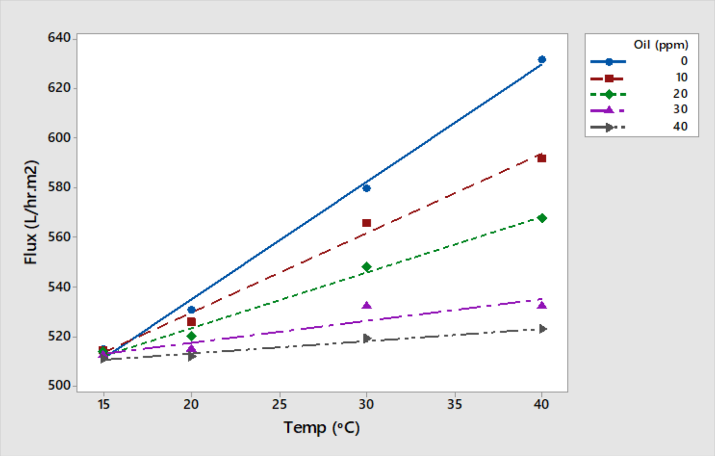

Figure 3 Effect of Temperature on UF Flux at Feed's Different Oil Content (P=2 bar).

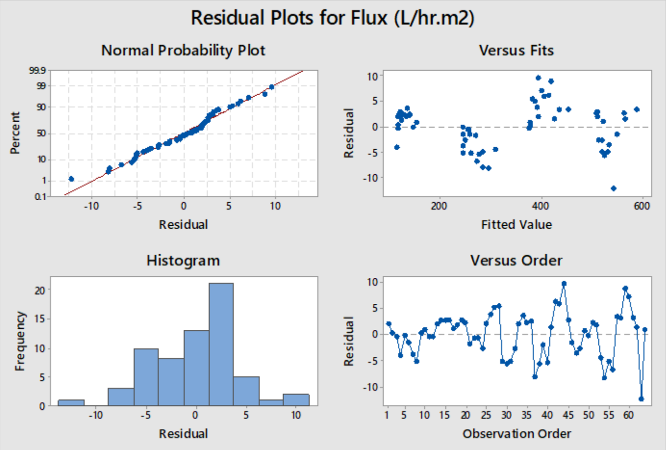

Figure 4 Residual Plots for Flux (J) of UF Process

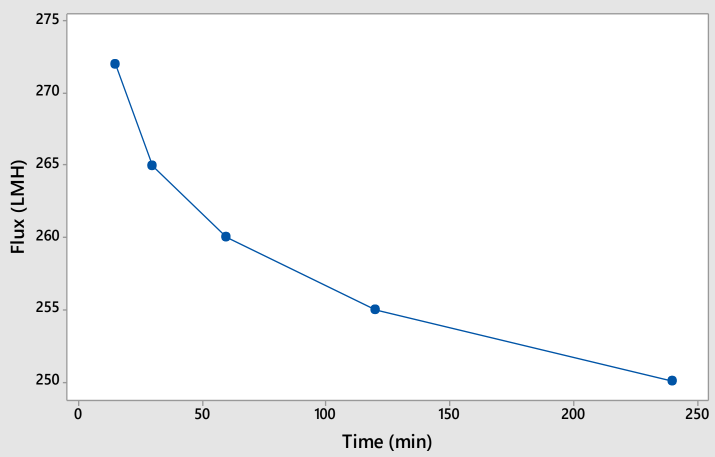

Figure 5 Flux of UF Process vs Time

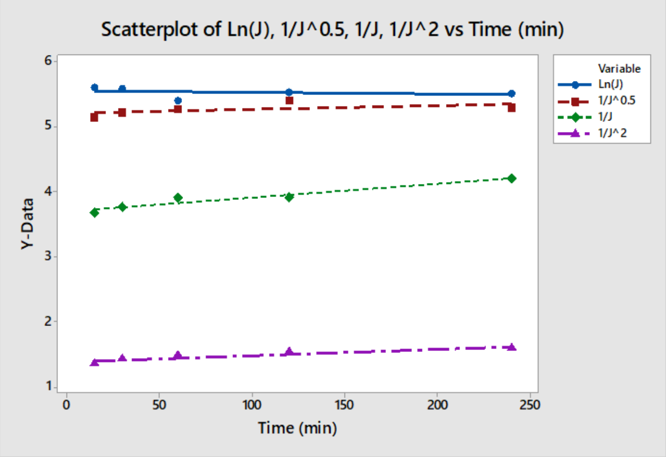

Figure 6 Different Forms of Flux for UF Process vs. Time

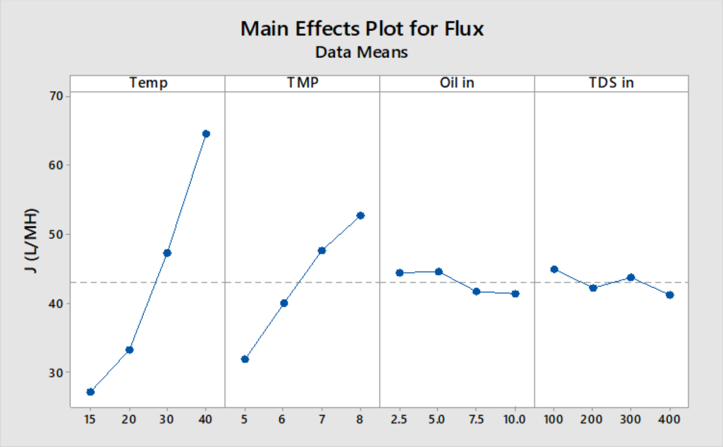

Figure 7 Main Effect Graph for the Flux of RO Process

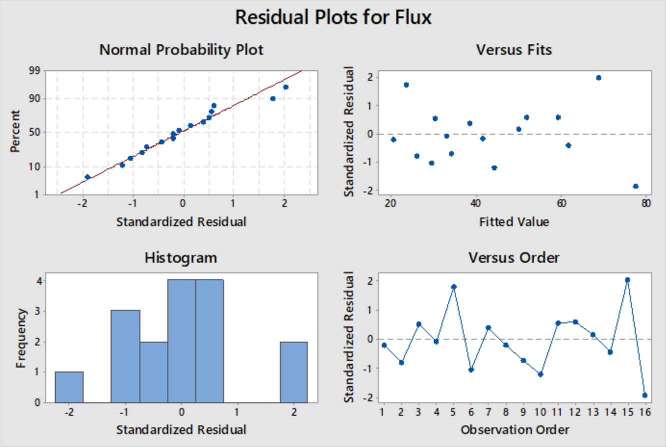

Figure 8 Residual Plots for Flux (J) of UF Process

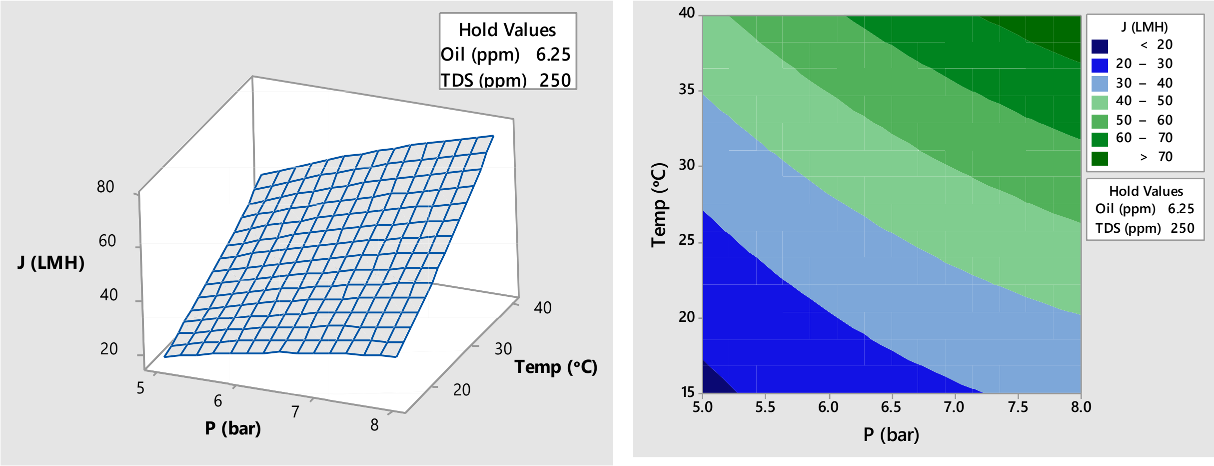

Figure 9 Flux of RO Process vs Temperature and Pressure

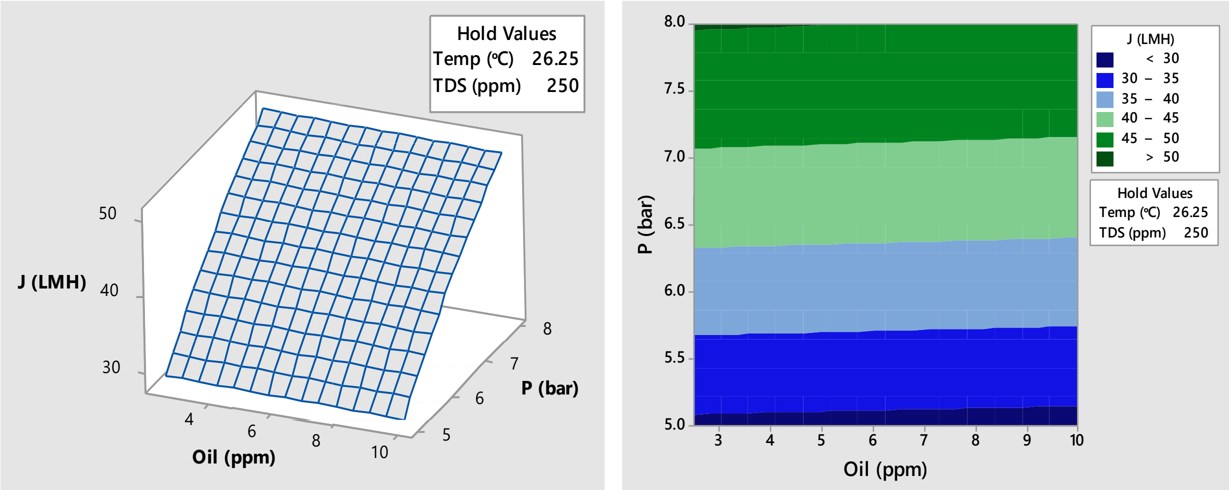

Figure 10 Flux of RO Process vs Oil and Pressure

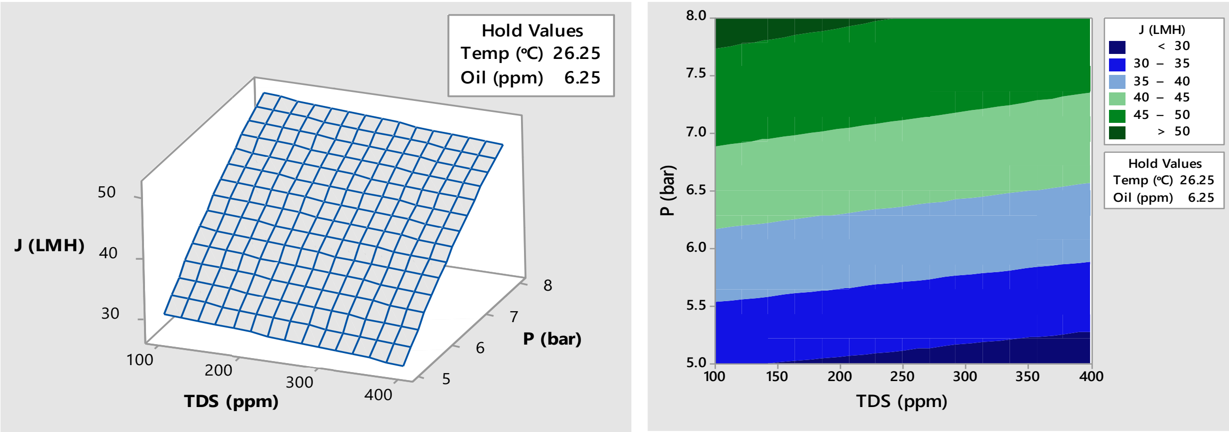

Figure 11 Flux of RO Process vs TDS and Pressure

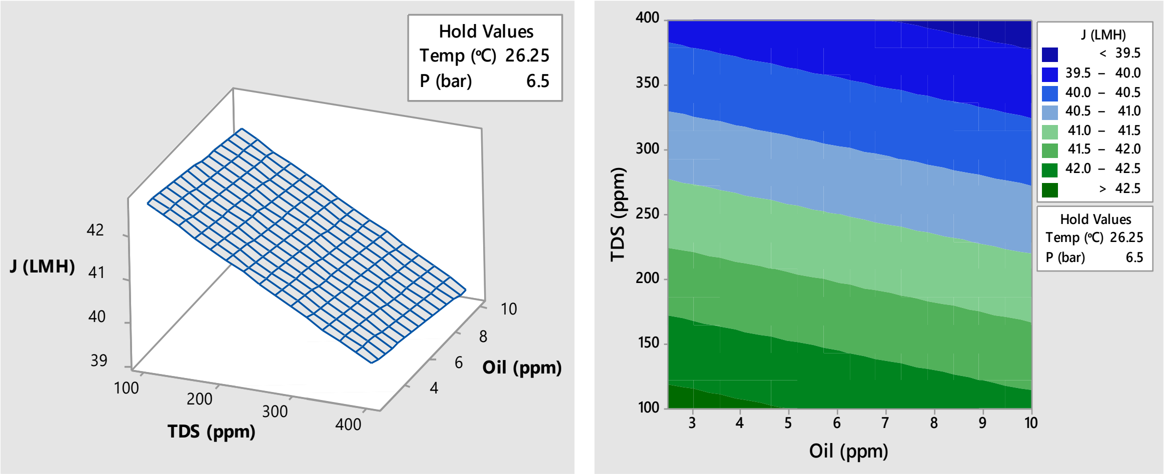

Figure 12 Flux of RO Process vs TDS and Oil

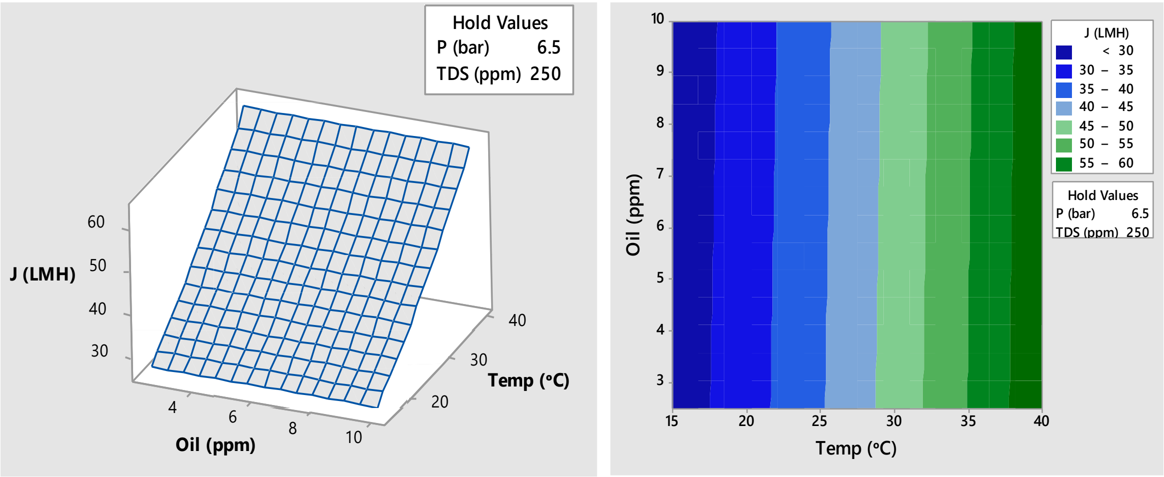

Figure 13 The Flux of RO Process vs Temperature and Oil

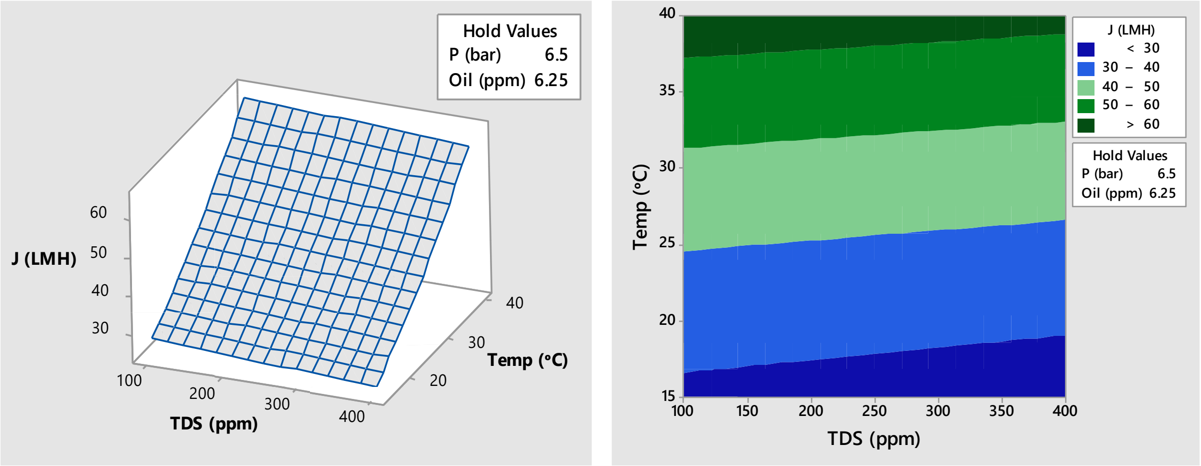

Figure 14 The Flux of RO Process vs TDS and Temperature

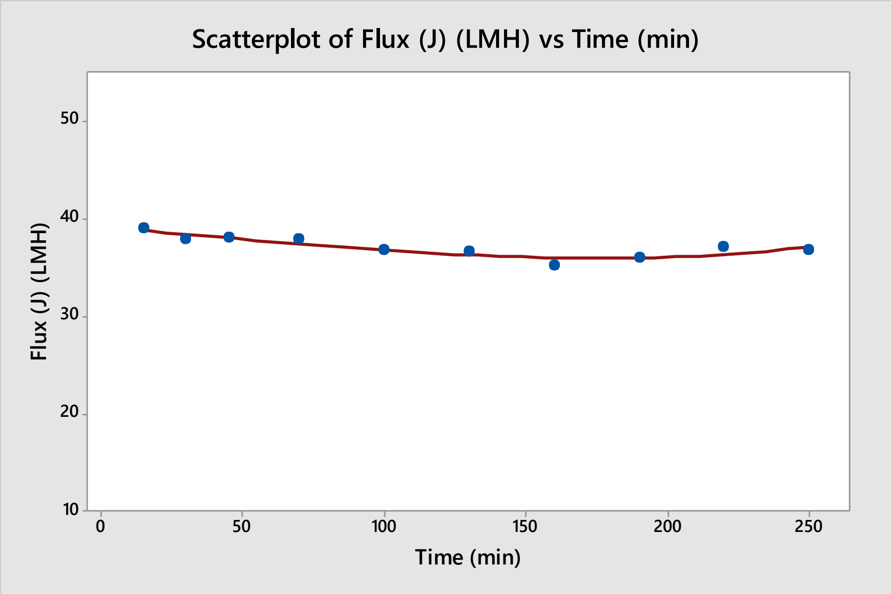

Figure 15 RO Flux vs Time, T= 25 C, P= 6 Bar, TDS = 200 ppm, Oil contents =5 ppm

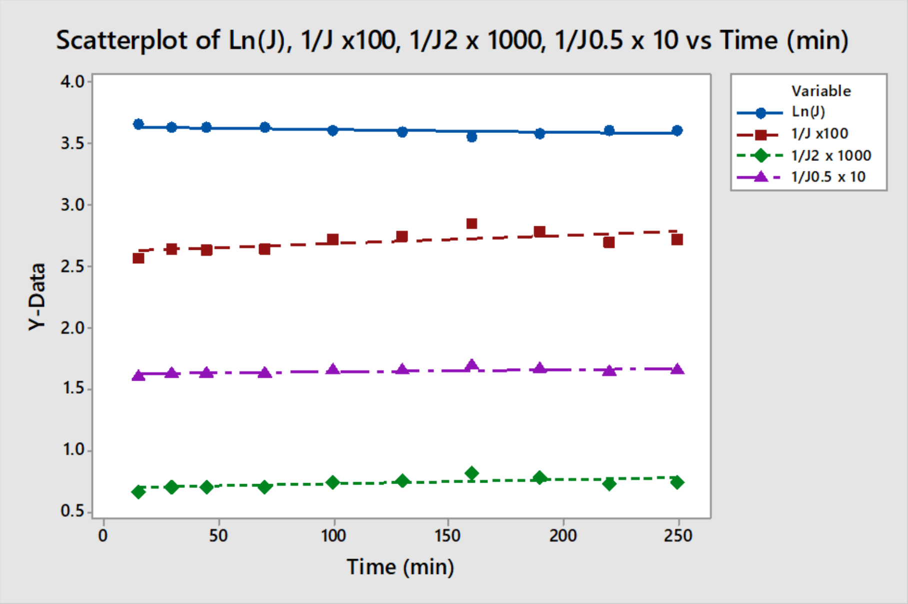

Figure 16 Different Mathematical Forms of RO Flux vs Time

Table 1 Summary of Characteristic Equations for Constant Pressure Filtration Laws

Model	**Fouling Mechanism**	**Reference**
$Ln(J) = Ln(J_0) - K_b t$	Complete pore blocking	**Susanto et al. 2009**
$1/J^{1/2} = 1/J_0^{1/2} - K_s t$	Standard pore blocking	**Vela et al. 2008**
$1/J = 1/J_0 - K_i t$	Intermediate pore blocking	**Kim et al. 1997**
$1/J^2 = 1/J_0^2 - K_c t$	Cake filtration	**Koltuniewicz et al. 1995**

Table 2 Factors Used in The Subject Experiment with Their Levels

	UF Process				**RO Process**			
Level **Factor**	**1**	**2**	**3**	**4**	**1**	**2**	**3**	**4**
Temp (°C)	15	20	30	40	15	20	30	40
P (bar)	0.5	1	1.5	2	5	6	7	8
TDS (ppm)	150	150	150	150	100	200	300	400
Oil (ppm)	10	20	30	40	2.5	5	7.5	10

Table 3 Analysis of Variables and Prediction Model UF Process

Source	**DF**	**Seq SS**	**Contribution**	**Adj SS**	**Adj MS**	**F-Value**	**P-Value**
Temp (°C)	1	17723	1.19%	849.6	849.6	48.76	0.000
P (bar)	1	1465218	98.27%	34784.8	34784.8	1996.42	0.000
Oil (ppm)	1	3839	0.26%	911.5	911.5	52.32	0.000
Temp (°C)*Temp (°C)	1	112	0.01%	111.5	111.5	6.40	0.014
P (bar)*P (bar)	1	76	0.01%	75.7	75.7	4.34	0.042
Temp (°C)*P (bar)	1	645	0.04%	644.9	644.9	37.01	0.000
Temp (°C)*Oil (ppm)	1	1774	0.12%	1774.4	1774.4	101.84	0.000
P (bar)*Oil (ppm)	1	664	0.04%	664.1	664.1	38.11	0.000
Error	55	958	0.06%	958.3	17.4		
Total	63	1491009	100.00%				
Model Summary							
S	R-sq	R-sq(adj)	PRESS	R-sq(pred)			
4.17415	99.94%	99.93%	1301.68	99.91%			
Regression Equation							
Flux (L/m^2.hr) = -82.71 + 3.342 Temp (°C) + 278.90 P (bar) + 1.239 Oil (ppm) - 0.02033 Temp (°C)*Temp (°C) - 4.35 P (bar)*P (bar) + 0.5914 Temp (°C)*P (bar) - 0.04905 Temp (°C)*Oil (ppm) - 0.5154 P (bar)*Oil (ppm)							

Table 4 Optimization Results for UF Process

Variable	**Setting**		
Temp (^oC)	40		
P (bar)	2		
Oil (ppm)	40		
Response	Fit	SE Fit	95% CI
Flux (L/hr.m^2)	527.44	4.54	(518.25, 536.64)

Table 5 Predicted vs Measured Optimization Results

Parameters	**Unit**	**Optimized value**	**Observed value**
Flux	L/hr.m^2	527.44	521.5
Oil Removal	%	-	97.1

Table 6 Orthogonal Array OA(L_{16}) for Taguchi RO Process and Experimental Results

No.	**Temp ^oC**	**Oil ppm**	**TDS ppm**	**P bar**	**Flux L/hr.m^2**	**TDS Removal%**	**Oil Removal%**
1	15	2.5	100	5	19.8	99.00%	100%
2	15	5.0	200	6	24.9	99.50%	100%
3	15	7.5	300	7	28.5	98.83%	100%
4	15	10.0	400	8	31.0	99.25%	100%
5	20	5.0	300	5	22.0	98.83%	100%
6	20	2.5	400	6	28.5	99.00%	100%
7	20	10.0	100	7	36.5	98.00%	100%
8	20	7.5	200	8	39.8	99.00%	100%
9	30	7.5	400	5	32.0	99.00%	100%
10	30	10.0	300	6	41.8	99.33%	100%
11	30	2.5	200	7	51.0	98.80%	100%
12	30	5.0	100	8	58.5	99.00%	100%
13	40	10.0	200	5	48.0	98.00%	100%
14	40	7.5	100	6	60.0	99.00%	100%
15	40	5.0	400	7	67.0	98.50%	100%
16	40	2.5	300	8	76.5	98.00%	100%

Table 7 ANOVA Analysis for Taguchi Method of RO Experiment

Analysis of Variance

Source	**DF**	**Seq SS**	**Contribution**	**Adj SS**	**Adj MS**	**F-Value**	**P-Value**
Temp (^{o}C)	1	3224.18	74.43%	3.8506	3.8506	104.72	0.000
P (bar)	1	978.60	22.59%	9.4253	9.4253	256.32	0.000
Oil (ppm)	1	57.12	1.32%	0.2306	0.2306	6.27	0.047
TDS (ppm)	1	23.98	0.55%	17.7025	17.7025	481.42	0.000
Temp (^{o}C)*Temp (^{o}C)	1	16.90	0.39%	16.9050	16.9050	459.73	0.000
P (bar)*P (bar)	1	7.02	0.16%	7.0225	7.0225	190.98	0.000
Temp (^{o}C)*P (bar)	1	23.87	0.55%	23.8694	23.8694	649.13	0.000
Error	8	0.29	0.01%	0.2942	0.0368		
Total	15	4331.98	100.00%				

Model Summary

S	R-sq	R-sq(adj)	PRESS	R-sq(pred)
0.191759	99.99%	99.99%	1.03043	99.98%

Regression Equation

J (L/m^2.hr) = -23.26 - 0.6588 Temp (^{o}C) + 10.503 P (bar) - 0.0732 Oil (ppm) - 0.009492 TDS (ppm)
+ 0.015830 Temp (^{o}C)*Temp (^{o}C) - 0.6625 P (bar)*P (bar) + 0.19446 Temp (^{o}C)*P (bar)

Table 8 Optimization Results for RO Process

Variable	**Setting**		
Temp (°C)	26.25 ~27		
P (bar)	6.5		
Oil (ppm)	6.25~7		
TDS (ppm)	250		
Response	Fit	SE Fit	95% CI
Fouling resistance	0.00171	0.00192	(-0.00273, 0.00614)
J (L/m^2.hr)	40.981	0.103	(40.745, 41.218)

Table 9 Observed Vs. Predicted Values for Optimization Conditions

Response	**Predicted value**	**Observed value**	**Deviation from predicted value**
Flux (L/m^2.hr)	40.7	38.8	5%
TDS (ppm)	-	1	-
Oil(ppm)	-	0	-