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PERFORMANCE EVALUATION OF REVERSE OSMOSIS PROCESS BASED ON THE POTENTIAL SYNERGY OF (PROCESS DESIGN – RSM) METHODOLOGIES

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Abstract

Reverse Osmosis process is a desalination process for production high quality drinking and industrial water. For describing and modelling any production processes including RO process the data availability and accessibility is the first prerequisite. In the current work an idea is adopted of making a synergy between two software to form basis for new developments in data collection and analysis for studying and optimizing the parameters affecting the performance of RO facilities served in Kurdistan Region-Iraq. The first software is employed as a statistical tool used to optimize and model the effect of the RO operating variables employed in the investigated pilot plants. The second software is used for output data generation related to RO membrane information for membrane selection and process design and operation. The combined features of the two software are used to identify and optimize perfectly the effect of membrane age, % recovery, (concentration of salts, pH, temperature and pressure) of feed water and the rejected brine concentration. The results obtained showed that increasing the concentration of salts in feed water, % recovery, feed temperature, acidic feed pH and no. of stages affect inversely the performance of the process. Opposite effect was predicted for concentration of the rejected brine. The age of the membrane seemed of not significant on the factors investigated. The mathematical model estimated showed the effect of the three major factors; feed salt concentration, pressure and temperature, has been estimated with high regression factor confirming the best fitting of the model with the input data.

Keywords: Reverse Osmosis (RO); Optimization; Modelling; RSM; Process design; Synergy

1. INTRODUCTION

Desalination of water has been used for decades all over the world. It has been used to purify fresh water for medicinal, industrial, and home purposes since the early 1970s [1],[2]. Many nations, particularly those with severe water shortages, use water desalination as a source of supply.

Thermal distillation (evaporation) reverses osmosis (RO), electro dialysis, and vacuum freezing are some of the water desalination methods that have been developed. Evaporation and membrane techniques, on the other hand, are the two most extensively utilized desalination technologies. For brackish water, Reverse osmosis is by far the most extensively used procedure; for seawaters, Multi Stage Flash (MSF) remains the most widely used approach [3], [4]. Because of its cheap operating costs and capital investment, low energy consumption, low operating temperature, and low and quicker construction duration, RO has various benefits over other desalination systems [5]-[7]

An RO desalination plant consists of four major systems: (1) pre-treatment, (2) high-pressure pumps (for brackish water pressure fluctuates between 17 and 27 bar and for saltwater 52 to 69 bar), (3) membrane systems, and (4) post-treatment (Davenport et al., 2018). The pre-treatment system removes all suspended particles to reduce salt precipitation and microbial development on the membranes. For pre-treatment, traditional methods (a chemical input followed by coagulation, flocculation, sedimentation, and sand filtration) or membrane processes ((MF) micro filtration and (UF) ultrafiltration) can be utilized [7], [9]

Membrane systems that allow feed water to pass through are made up of a pressure vessel and a semi-permeable membrane. For the RO process, any selectively permeable membrane material can be employed; nevertheless, the kind of membrane and membrane orientation are critical factors in the RO process' effectiveness [9]-[11].

Several designs are available for making RO membrane and elements [12], [13]. Plate and frame, tubular, hollow-fibre, and spiral-wound membrane module configurations are all available. The spiral-wound membrane module arrangement is the most popular element device for RO membrane use [12], [14]. A flat sheet of thin composite membranes with an active polymer layer (high permeability but impermeable to dissolved salts and particulate matter) supported by a porous polymer layer wrapped around a central collecting tube is typically used to make the membranes [12], [13].

The performance of the (RO) process is influenced by a number of factors. These variables may be classified into three categories: feed water properties, operational circumstances, and system setup. The key parameters are permeating flux and salt retention, which are determined primarily by the feed water's pressure, temperature, recovery, and salt concentration [12]. Researchers have devised a variety of methods for lowering the energy cost of RO plants, including enhancing membrane performance, developing more accurate performance models, creating more energy-efficient flow sheets, and optimizing the system's operation [15], [16].

Optimization the design and operating parameters of RO process were the themes of several studies [1],[6],[18]-[20]. Operating parameter value optimization has already been used to enhance designs, efficiency, and operational safety. The use of several mathematical programming approaches to determine the best parameter values for RO plants has been addressed elsewhere [21].

The use of software-based computer models for forecasting membrane performance and aiding in the design of membrane water treatment plants is an alternate way for predicting membrane performance and assisting in the design of membrane water treatment plants. Nonetheless, due to a lack of operational data, the operating variables and performance models were incorrectly optimized [23].

The core of this paper lies at the optimization and modeling the effect of some design and operating variables of seven full-scale RO membrane facilities in Kurdistan Region-Iraq which were surveyed for data collection. The data availability and accessibility is the first prerequisite for

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describing and modeling production processes. In connection, owing to lack of the required data from the surveyed RO pilot plants, we adopt the idea of making a synergy between two software taking into account the software features that are used to expand each other's functionality so that they can be the basis for new developments in data collection and analysis. The first software used is a statistical tool operates based on RSM. It was used to optimize and model the effect of the RO operating variables. The second software is the IMSDesign Hydranautics software that was used for output generation related to RO membrane information for membrane selection and process design and operation. The combined features of two software were used to optimize and model perfectly the effect of membrane age, TDS and pH, temperature of feed water, % recovery and pressure on plant performance presented by permeate TDS and salt concentration in the rejected brine.

2.1 EXPERIMENTAL WORK

2.1.1 The Analytical Method

The approach used in this work merely relies on information and data collected from several RO pilot plants in Kurdistan region-Iraq. The data collected include ranges of applied pressure, temperature, type and TDS of the feed water. The data were used as sources of independent variables that were used as input to 16 experiments designed based on RSM using a statistical technique able to capture and represent the relationships between input-output variables. The input data of the 16 designed experiments were fed to the IMSDesign RO software to be processed and analyzed by the software to determine the efficiency and the performance of RO process of identified membrane specifications. The performance of the RO process is represented by the TDS of permeates and rejected brine calculated and estimated by the IMSDesign RO software. The estimated results were fed again to the statistical software to be analyzed as responses using ANOVA for optimization and modeling.

The RO membrane employed in this work was Espa_ld_4040. It is low fouling spiral wound polymeric membrane (Composite Polyamide Membrane). The active Area: 80 ft2 (7.43 m2) Feed Spacer: 34 mil (0.86 mm). Fig. 1 shows the membrane features.

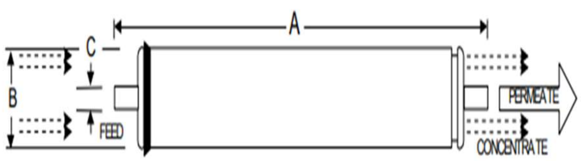

Figure1. RO membrane configuration and dimensions

A, inches (mm): 40.0 (1016), B, inches (mm): 3.95 (100.3), C, inches (mm): 0.75 (19.1)

Maximum Applied Pressure: 600 psig (4.14 MPa), Maximum Chlorine Concentration: < 0.1 ppm, Maximum Operating Temperature: 113 °F (45 °C), pH Range, Continuous (Cleaning): 2-10 (1-12), Maximum Feed-water Turbidity: 1.0 NTU, Maximum Feed-water SDI (15 mins): 5.0 , Maximum Feed Flow: 16 gpm (3.6 m3 /h),Minimum Brine Flow: 3 gpm (0.7 m3 /h), Maximum Pressure Drop for Each Element: 15 psi (0.10 MPa).

In multiple stage RO system, the concentrate from a stage becomes the feed water to the next stage. The permeate water that is collected from the stages is combined such as using additional stages resulted in increasing the recovery of the system. The investigated RO pilot plants operate at pressure range (14-16) bar. The type of feed water is undeveloped brackish groundwater aquifers; the concentration of salts in the feed water is up to 950 mg/l.(Anis, Hashaikeh and Hilal, 2019)

3.1 EXPERIMENTAL DESIGN

Series of experimental were designed using central composite design based on RSM methodology as shown in Table 1. The operating conditions using RO membrane process are feed water TDS (632-968) mg/l, Temperature of feed (8.2-42) ºC, Operating Pressure (13.3-16.7) bar.
A quadratic polynomial model design was fitted to evaluate the effect of each independent variable to the responses. The empirical equation is written as:

$$Y=\beta_0+\beta_1x_1+\beta_2x_2+\beta_3x_3+\beta_{11}x_1^2+\beta_{22}x_2^2+\beta_{33}x_3^2+\beta_{12}x_1x_2+\beta_{13}x_1x_3+\beta_{23}x_2x_3 \quad (1)$$

The response (Y) was correlated to the set of regression coefficients (β): the model intercept is (β_0), β1, β2, β3 are linear terms, β12, β13, β23 are interaction terms and β11, β22, and β33 are quadratic coefficient terms. The design expert portable statgraphics centurion 15.2.11.0.exe software was used for the regression and graphical analysis of data. The actual levels of the operating variables of the 16 experiments are listed in table1.

The Performance evaluation is based on determination of water quality from RO unit based on determination of Permeate water salinity which is measured as TDS. The simulation of RO processes conducted under similar operating conditions of 800mg/l TDS of feed water, 20 m³/h permeate flow, 15 bar as feed water pump pressure respectively. The selection of these parameters is based on the upper and lower guidelines of the RO pilot plants investigated.

Table1. The actual levels of the operating variables of the 16 experiments

Exp.	Pressure (bar)	Temp (ºC)	Feed water TDS (mg/l)	Permeate TDS(mg/l) Membrane age = 1 year	Permeate TDS(mg/l) Membrane age = 3 years
1	14	35	700	109.97	114.56
2	16	15	900	68.47	73.59
3	15	25	632	58.8	65.52

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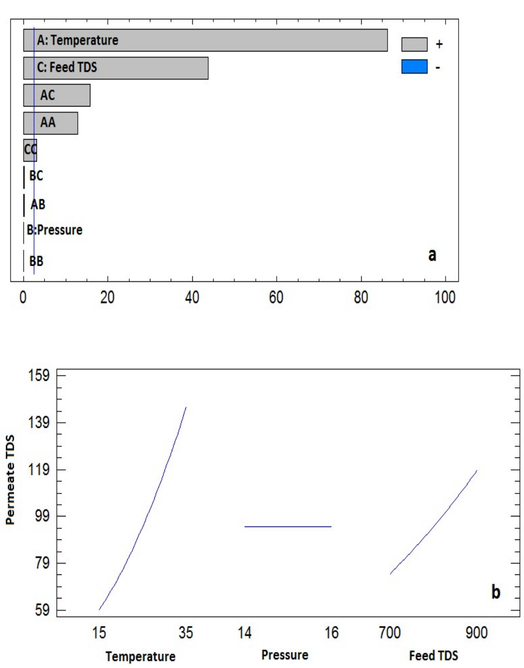
4	16	35	700	109.83	114.32
5	16.7	25	800	90.46	94.75
6	13.3	25	800	90.55	95.05
7	15	25	800	90.28	94.73
8	15	25	800	90.28	94.73
9	15	25	968	130.77	135.04
10	16	15	700	44.03	47.96
11	14	15	900	68.32	73.08
12	14	35	900	174.82	181.28
13	15	42	800	181.09	189.84
14	15	8.2	800	40.33	44.36
15	16	35	900	174.74	181.61
16	14	15	700	44.1	47.87

4.1 RESULT AND DISCUSSION

4.1.1 Analysis of the results using ANOVA

Optimization for the operating variables was done using RSM. The response data were analyzed using the design software, that gives ANOVA and regression equations that explains the interactive effects of variables. The obtained results are further justified by the Pareto chart and normal plot of the standardized effect, response surface and contour plots. The Pareto chart shows variations of the mean among the high and low values of each factor. The magnitude of slope represents the intensity of the effects that each factor exerts. When the slope is positive, the response increases for higher levels of that factor and vice-versa [24],[25]. Figure 2 illustrates the experimental design analysis results of the permeate TDS data.



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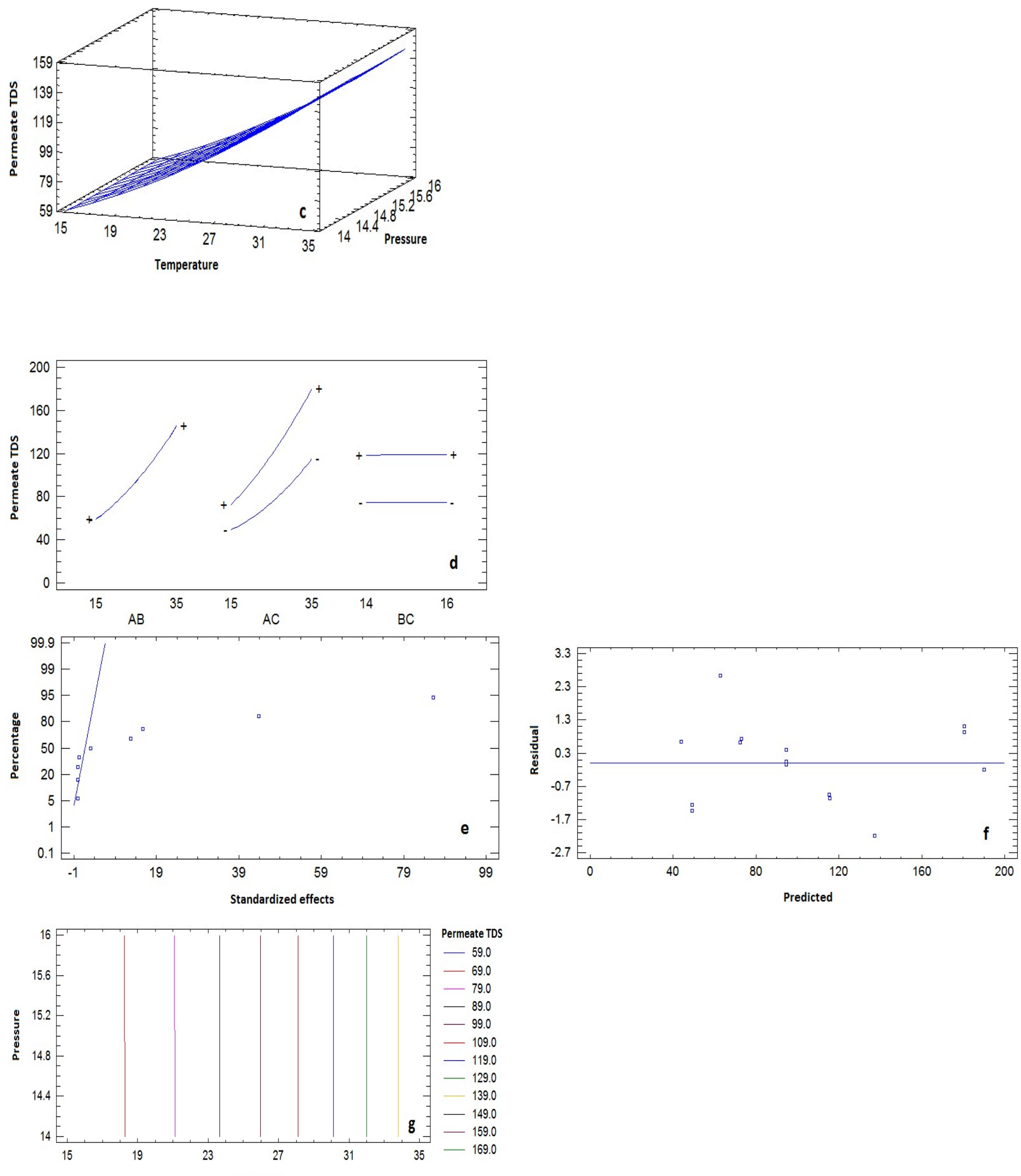

Figure2. Pareto chart (a), Standardized effects plot (b), Interaction plots (c) , 3-D Response surface (d), Normal probability plot (e), Normal residual plot (f), 2-D counter plot of response surface (g) for Permeate TDS.

The analysis of the permeate TDS data gave p-values less than 0.05 that specifies the significant terms in the model. The estimated p-values confirm that the model was statically sound. The Pareto chart (Fig. 2.1a) shows the significant effect of temperature and feed water TDS, while pressure shows no significance. The positive slope of the effect of temperature and feed water TDS

revealed that permeate TDS increased with increasing the two variables. The main plot effects (Fig. 2.1b) shows that the quality of permeate decreases with increasing the temperature and feed water TDS. The permeate TDS increases by increasing feed water salts concentration and its temperature. However, the remarkable and more sharper increase in permeate TDS is observed when temperature increases.
The response surface correlations of the variables are shown (Fig. 2.1c). The Figure shows surface plot of the mean response (permeate TDS) as a function of the operating variables.
No interactive effect between pressure and temperature and between pressure and feed water TDS at the studied levels of the variables is observed as shown in (Fig. 2.1d). The situation is reflected by the parallel lines of the effects of the two variables.
The normal probability plot (Fig. 2.1e) shows that the data are assigned normally, as most of the points are closer to the straight line which represents an acceptable contract between the real data and the ones obtained from the model. The normal residual plot (Fig. 2.1f) showed that the actual and predicted values lie nearer to each other representing no major violations of the underlying assumptions. The insignificant interactions between the operating variables were more justified by the non-elliptical nature of the contour plots (Fig. 2.1g).
On the other hand, the coefficient value R^2= 99.847 shows a high correlation between the actual and predicted values. The generated empirical regression model equation using the experimental data is shown in equation (2):

Permeate TDS = 196.949 - 7.79 T – 0.66 P - 0.36 S + 0.078 T^2 - 0.0066 PT + 0.01 TS - 0.00389 P^2 + 0.0012 S + 0.00019S^2	(2)

Where T: Feed water temperature (ºC), P: Pressure (bar), S: Feed water TDS (mg/l).

The numerical optimization predicted that the maximum value of permeate TDS=261.848 is obtained when feed pressure = 14.43, feed temperature = 41.82 ºC and feed water TDS = 968.18.

5.1 DATA ANALYSIS USING IMSDESIGN

The estimated values of Permeate TDS from ANOVA were used among the data inputs to the IMSDesign software to investigate the effect of feed temperature, feed water pH, % recovery, % of feed TDS and age of the membrane on RO process performance represented by Permeate TDS and TDS of the rejected brine. The data obtained were analyzed and correlated in forms of histograms plots.Fig.3 and Fig.4 correlate the data of salt concentration in feed water and permeate water for 3 stage RO process using membranes age of 1 year and 3 years respectively.

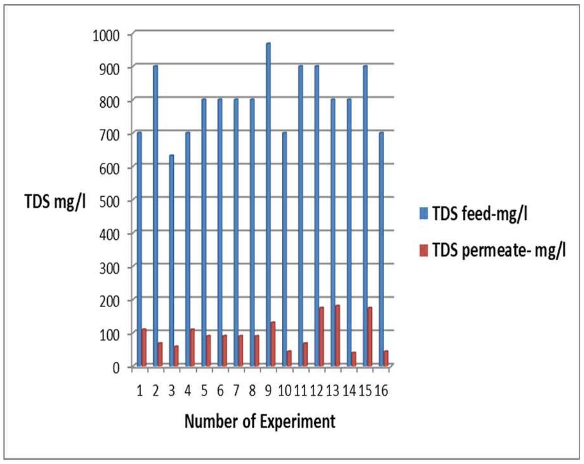

Figure3. TDS of permeate and feed (mg/l) for 3 stages RO process, membranes age=1 year

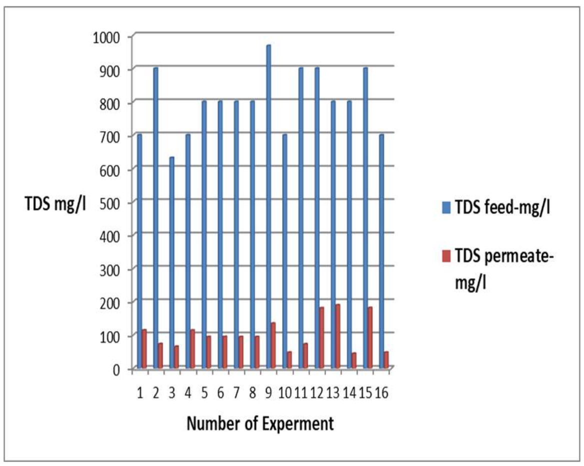

Figure4. TDS of permeate and feed (mg/l) for 3 stages RO process, membranes age=3 year

The results showed that there is no significant effect of membrane age on the RO process performance.

The effect of feed water temperature on RO process performance for three stage RO process with membranes of age 1and 3 year is shown in Fig. 5 and Fig.6. It can be seen that the permeate TDS increases with increasing feed temperature from 4 to 42 ^{o} Cat all different pH. The reason of this effect is attributed to the decrease of feed water viscosity which leads to decrease of fouling on the membrane, but solute diffusivity and solution osmotic pressure increase with increasing feed water temperature [17]. Solvent and solute permeation increase with temperature, which leads to lower applied pressure and observed rejection [17],[26]**.**

On the other hand, using feed water with acidic pH (4.7) has negative effect on the performance TDS as shown in Fig 6. While no effect on the RO performance when feed water is neutral or slightly basic, the membrane is negatively charged at high pH due to the deprotonating of carboxylic groups and adsorption of hydroxide ions on the membrane surface. The charge changes only marginally when pH decreases throughout the basic and neutral areas, but rises rapidly below pH 6 to reach the isoelectric point (IEP) [27].

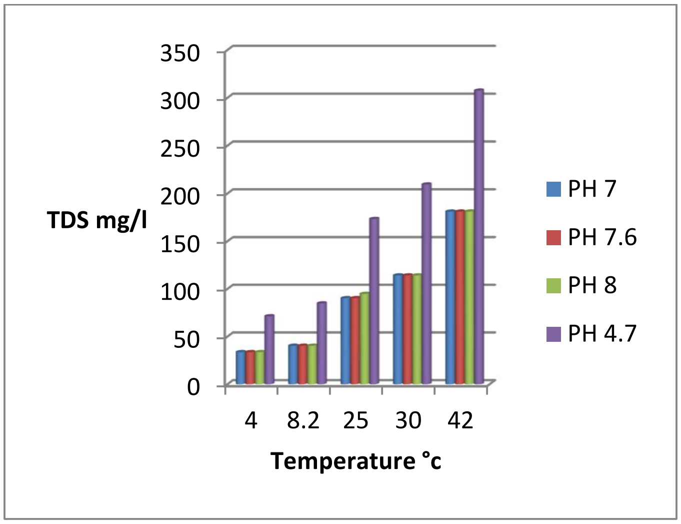

Figure5. Permeate TDS versus Temperature for different % recovery at 15 bar, Feed TDS (800 mg/l), 3 stages process, membranes age= 1 year

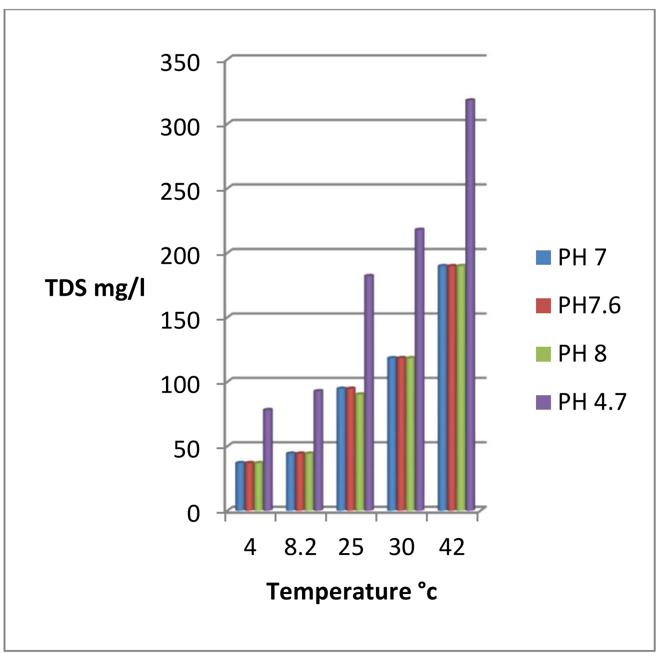

Figure6. Permeate TDS versus Temperature at constant pressure (15 bar) and constant Feed TDS (800 mg/l) at PH 7, 7.6, 8, and 4.7 for 3 stages Ro process with membranes age= 3 year

It is worthy to note that membrane's recovery can decrease with the passage of time due to many factors, but recovery rate should not be more than the design capacity. The effect of % recovery

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and temperature on RO process performance is shown in Figs.7 and 8. The results showed that operating at low feed water temperatures and low % recovery has minor effect on Permeate TDS. The effect of % recovery on permeates TDS become more distinct and negative when the system operates at high feed water temperature. In spite of increasing the recovery resulted in wasting less water to drain[28]. However, the disadvantages are poorer permeate quality, shorter RO membrane life depending on the quality of the feed water [29].

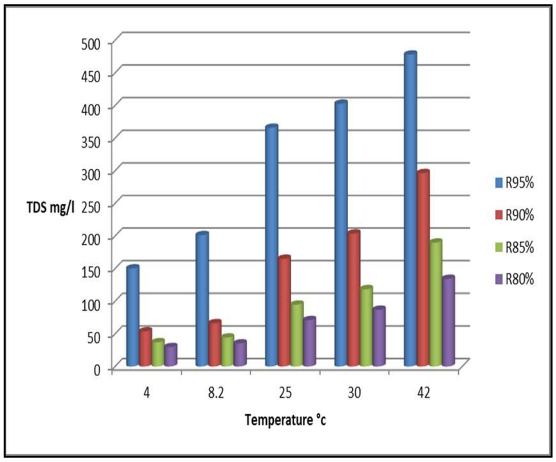

Figure7. Permeate TDS versus Temperature for different % recovery at 15 bar, Feed TDS (800 mg/l), 3 stages process membranes age= 3 years

As discussed earlier, higher salt concentration of feed water lead to increase the amount of salt passage and decreasing the permeate flow owing to increasing the osmosis pressure, decreasing NDP (Net Driving Pressure) this will result in increasing the permeate TDS [30] as shown in Fis.8 and 9, and the concentration of the salts in the brine as shown in Figs 10 and 11. The effect of membrane age is also reflected in the figures.

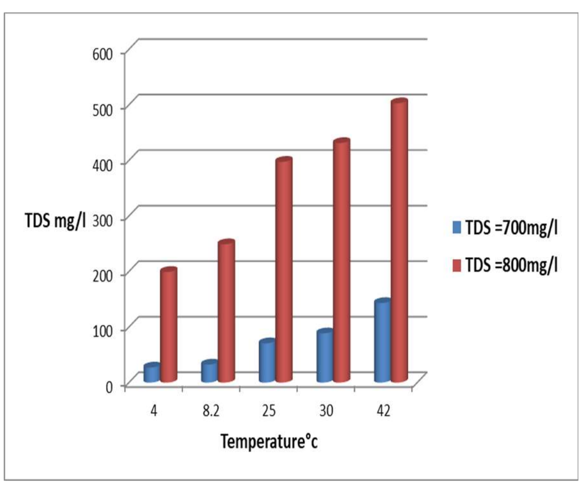

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Figure8. Permeate TDS versus different temperature at 700-800 mg/l feed TDS at 3 stage process, and membrane age = 1 year

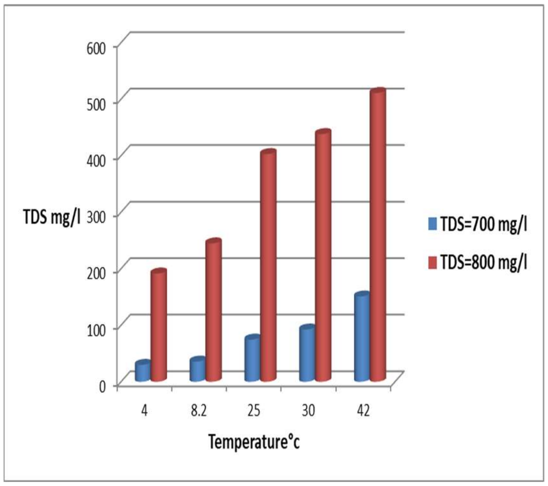

Figure9. Permeate TDS versus different temperature at 700-800 mg/l feed TDS at 3 stage process, and membrane age = 3 year

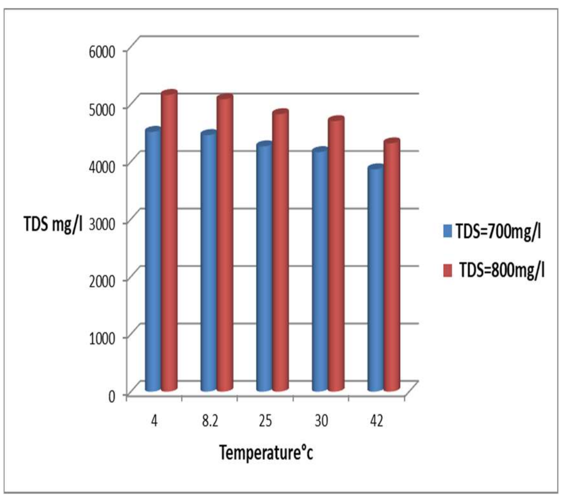

Figure10. Brine TDS versus different temperature at 700-800 mg/l feed TDS at 3 stage process, and membrane age = 1 year

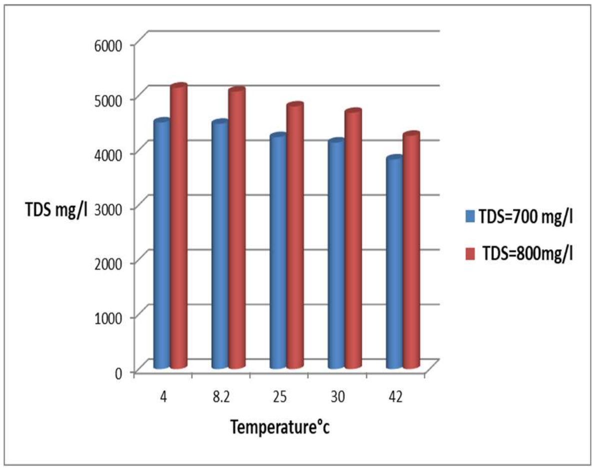

Figure11. Brine TDS versus different temperature at 700-800 mg/l feed TDS at 3 stage process, and membrane age = 3 year

CONCLUSION

The use of software-based computer models is an effective method for predicting membrane performance and assisting in the design of membrane water treatment plants as well as optimization of the operating variables in particular when sufficient experimental operation data are not available. Moreover, achieving the above goals by using the combined functions of more than one software could be considered as more efficient tool. In this direction, the hybridization of the functionalities of optimization and modeling of RSM and data simulation and analysis of IMSDesign software seemed a reliable and competent mode to predict the performance of RO process.

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