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Nanofiltration and calcium sulfate limitation for top brine temperature in Gulf desalination plants

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Abstract

All MSF desalination plants have been operated at a top brine temperature below 120°C. That is because of sulfate scaling phenomena, which usually occurs when the temperature is higher than 120°C. This type of scaling is hard scale that cannot be removed easily by chemical or mechanical cleaning. In the recent years desalination technology has created a new type of membranes that can overcome sulfate scaling. These new type of membranes is a nanofiltration membrane (NF). NF membranes have the ability to remove the sulfate and calcium ions in seawater feed, as a result the risk for sulfate scaling is eliminated. This paper mainly aims to study the scaling potential of $CaCO_3$, $CaSO_4$, $BaSO_4$, SrSO4, silica and CaF at different productivity with a nanofiltration product water and compare it with the scaling potential of normal seawater. This paper also studies the maximum possible percentage inhibition for $CaSO_4$ using nanofiltration product water, if this water is used as a feed for a MSF unit. Acidification process has been also tried at different dosing to increase the % inhibition for $CaCO_3$ scaling. The result indicated a great percentage inhibition for $CaSO_4$ scale using a nanofiltration membrane. The inhibition reached 99.1% at 35% productivity and decreased to about 96.98% at 75% productivity without addition of any antiscalant or chemicals. The result also show a low prevention for $CaCO_3$ scaling started from 23.41% inhibition at 10% productivity and decrease to about 5.3% at 75% productivity. Also for all other scaling constitutes, a great scaling inhibition was found — about 97.7% for BaSO4, 99.8% for $SrSO_4$ scaling and 94.86% inhibition for CaF scaling at 50% conversion. This study proved the reliability of a nanofiltration system in preventing all types of scaling in the Gulf seawater, which can be considered as a revolution in the MSF plants when applied at high operation temperature.

Keywords: Nanofiltration; Sulfate scaling; Calcium carbonate; Ion product; Solubility product

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1. Introduction

Desalination process suffers mainly from different types of scaling, as calcium carbonate, magnesium hydroxide and calcium sulfate scaling. Calcium carbonate scaling was controlled by two methods — antiscalants or acid treatment, but calcium sulfate scaling cannot be controlled by any types of antiscalants, also it cannot be removed easily by any type of chemical or mechanical cleaning due its hardness. The only method that is always applied in desalination plants to control calcium sulfate scaling is the control of the top brine temperature and the brine concentration limit. Although as the temperature increases, the solubility of calcium sulfate scaling decreases and its attendances to precipitate increases, it was found that below 120°C and at brine concentration of 1.6 for seawater calcium sulfate cannot precipitate at desalination plants [1].

This limit temperature and concentration factor can be avoided totally, if a new technique is used to prevent calcium sulfate scaling — a nanofiltration membrane system. In desalination plants, with the increase of the top brine temperature more benefit and advantages can be obtained.

2. Advantages of high temperature operation

The driving force for the MSF process — the differences between top brine temperature and the brine blowdown temperature (flash range), is set by the calcium sulfate barrier. Any attempt to increase the flashing rage will result in a great economical benefit to the desalination plants, because this will result in decreasing the number of stages and consequently decrease of the heat transfer area. This also will maximize the performance ratio by lowering the amount of steam required. The top brine temperature in MSF plants can been increased by the new generation of nanofiltration membranes to more than 120°C [2]. A move towards high temperature operation and use of high temperature antiscalant must be anticipated. The decision to use the nanofiltration membrane before MSF plants can be considered more economical, especially when one considers the massive desalination plants being built these days [3].

3. Nanofiltration system

A nanofiltration system is a membrane separation technique similar to reverse osmosis (RO), but a pressure driven process is applied in the area between the separation capabilities of RO and ultrafiltration (UF) membranes [4]. NF systems typically operate at lower pressure than RO, but yield higher flow rates of water, although of different quality compared to RO. The nanofiltration membrane is used when a high sodium rejection is not needed, but where other salts as Mg and Ca (i.e. divalent ions) are to be removed. The main advantages of a nanofiltration system over a reverse osmosis one, is that it requires less energy and a lower operating pressure. The main aim of this paper is to study the NF system from the scaling potential side for a nanofiltration membrane unit.

4. Scaling potential of seawater before and after nanofiltration system

Scaling potential for a specific type of high salinity water can be characterized by many factors as Stiff and Davis saturation index for calcium carbonate scaling, solubility limits and ion product for each type of scaling — calcium sulfate, strontium sulfate and barium sulfate. In the Arabian Gulf area, natural seawater contains many ions in a high concentration — more than any other seawater types in other countries. This can increases the risk for scaling problem in desalination plants. More precaution should be attained in scaling potential calculations. Because of that, the scaling tendency for other types of scaling should be included in the scaling potential calculations.

Other main types of scaling that must be included in scaling potential are barium sulfate and strontium sulfate scaling, besides the old calcium carbonate and calcium sulfate scaling.

4.1. Calcium carbonate scaling potential

Calcium carbonate scaling potential can be specified by Stiff and Davis saturation index. The method of calculation and all the equation used can be illustrated by the following equations

$$\text{S\&DSI} = \text{pH}_b - \text{pH}_s \quad (1)$$

$$\text{pH}_s = p(\text{Ca}_b) + (p\ \text{alk}_b) + K \quad (2)$$

where pH_b is pH value of the concentrated stream; pH_s is pH saturation at which saturation of $CaCO_3$ occurs; $p(\text{Ca}_b)$ — negative $\log_{10}$of molarity concentration (mol/l) of calcium in the concentrated stream; (p alk_b) — negative $\log_{10}$ of molarity concentration (mol/l) of total alkalinity in the concentrated stream; K — ionic strength constant at 25°C as a function of the ionic strength.

$$\text{pH}_b = 6.3 + \log R_b \quad (3)$$

where R_b is concentration of HCO_3^- (as mg/l in the brine stream)/(CO_2 as mg/l in the brine stream). If the value of S&DSI is negative, this indicates that no $CaCO_3$ precipitation will occur and $CaCO_3$ tends to dissolve, but if this value is positive, then pretreatment is required.

4.2. Sulfate scaling

Sulfate scaling includes calcium sulfate scaling, barium sulfate scaling, and strontium sulfate scaling. To determine if sulfate scaling will cause scaling or not, calculations are made to determine if the solubility product of these salts will be exceeded or not in the concentrated stream. Each solubility product (K_{sp}) is compared respectively with its ion product (IP) in the concentrated stream.

$$\text{IP}(mx) = \left(C_{m^+}\right)^p \cdot \left(C_{x^-}\right)^q \quad (4)$$

C_{m^+} is the molar concentration of positive cations of the scaling compound; C_{x^-} — the molar concentration of negative anions of the scaling compound; mx — the scaling compound.

If the K_{sp} is equal to (IP) the solution is saturated, but when K_{sp} is less than (IP) precipitation will occur, whereas if K_{sp} is greater than (IP) the solution is unsaturated, and no precipitation will be expected to occur.

For all these types of scaling, scaling potential will be studied without adding acid and with acid treatment to reduce the calcium carbonate scaling risk.

4.3. Calcium fluoride scaling

Calculate ion product (IP_{CaF}) of calcium florid, then if the IP_{CaF} is greater than 4.0×10^{-11}, there will be a chance for calcium fluoride to precipitate. While if the IP_{CaF} is less than 4.0×10^{-11}, then there will be no chance for calcium fluoride to precipitate [5].

5. Scaling potential after acid treatment

The following change is required in calculation as in the following reaction

$$2HCO_3^- + H_2SO_4 \rightarrow 2H_2O + 2CO_2 + SO_4$$

Every ppm of bicarbonate as ppm $CaCO_3$ forms 0.88 ppm carbon dioxide as CO_2 after sulfuric acid addition [6]. The main step required to calculate the alkalinity after acid is by using Eqs. (5) and (6).

$$R\ \text{(before acid)} = A/Z \quad (5)$$

$$R\ \text{(after acid)} = X/\left(Z + 0.88(A - X)\right) \quad (6)$$

where A is alkalinity of feed as ppm $CaCO_3$ before acidification; X — alkalinity of feed as ppm $CaCO_3$ after acidification; Z — free CO_2 as ppm CO_2 in feed.

First the new desired pH value specified is, then the new values of R are calculated from Eq. (7).

$$R = 10(\mathrm{pH} - 6.3) \tag{7}$$

$$X = \frac{(R_{\mathrm{after}} \cdot Z) + R_{\mathrm{after}} \cdot 0.88 \cdot A}{1 - (R_{\mathrm{after}} \cdot 0.88)} \tag{8}$$

The calculation will focus on scaling potential of nanofiltration product water as it was used as a makeup water for MSF plant, first calculating the new composition of the brine produce by distillation as it was concentrated more and more, when moving from one stage to another assuming the worst condition to be established. Starting from concentration factor (CF) 1.1 for brine produced till CF 2 and more.

After calculating the new composition of the different types of brines, the scaling potentials for these brines were calculated based on many parameters as ion product (IP), solubility product (SP) and Stiff and Davis saturation index (S&DSI). All these parameters have been calculated for calcium carbonate, calcium sulfate, strontium sulfate and barium sulfate. While for silica scaling the potential for scaling was based on comparing the concentration of silica in the brine with calculated values. Calcium fluoride scaling is also based on comparing the ion product with constant values as in the calculation procedures.

The paper will mainly compare the scaling potential of normal brine at different concentrations and the nanofiltration product also at different concentration factors, before and after acidification. The base of comparison will be only the potential for different types of scaling.

6. The experiment description

A nanofiltration membrane process was integrated with the MSF unit, the experimental work has been carried out at the Saline Water Conversion Corporation, Research and Development Center, Al-Jubail, Kingdom of Saudi Arabia. In this trial NF permeate was used as makeup to a multi-stage flash (MSF) pilot plant at a flow rate of 1.5 m^3/h replacing normal seawater with nanofiltration product water as a makeup water. The test has been carried out with acid and without acid. Table 1 represents the feed water chemical composition as it fed to the RO system and the chemical composition of the nanofiltration product water, that is fed as a makeup water to the MSF unit. The NF unit consists of a high-pressure pump and five NF modules arranged in a series. The experiment proved that the combination of NF product water with the MSF enables operating MSF unit at high distillation temperature, with high distillate recovery. But this paper mainly studied the product water from the scaling side.

7. Calculations and results

Table 1 shows the seawater feed composition at Saudi and the NF product composition as tested in Saudi Arabia. These NF membrane types have been tested in Saudi Arabia using Jeddah seawater as a feed to nanofiltration seawater and the product of nanofiltration was used as a makeup to a MSF plant operated in real operation at 160°C as top brine temperature. More details on the test can be found in [1,2]. Tables 2 and 3 show the scaling potential for calcium carbonate scaling. Table 4 specifies the percentage inhibition of calcium sulfate scaling, while Tables 5–7 describe the scaling potential for strontium sulfate, barium sulfate, and calcium florid scaling. Table 8 shows the potential for silica scaling, and Table 9 shows the scaling potential for calcium carbonate scaling after acidification at different proposed pH values. Figs. 1–6 summarize the results of these tables. Fig. 7 represents the proposed acidification process.

8. Results and discussion

Table 1 shows that although the total dissolved solid (TDS) of Saudi Arabian feed is very high

Table 1
The composition of feed and product of nanofiltration membranes and % removal as a result of the Saudi experiment

Analytical parameter, mg/l	Feed to nanofiltration system	Ref.	Product of a nanofiltration membrane	Ref. analysis	% removal
pH	8.2	[1]	7.85	[1]	
TDS	44046	[1]	27720	[1]	37
T. alkalinity	128	[1]	46	[1]	64.06
CO_3^-	<0.1	[1]	<0.1	[1]	
HCO_3^-	128	[1]	46	[1]	64.06
CO_2	9	[2]	20	[2]	
Na^+	12,860	[1]	9426	[1]	26.70
K^+	490		150	[2]	69.39
Mg^{2+}	1608	[1]	193	[1]	88.00
Ca^{2+}	481	[1]	93	[1]	80.67
Al^{3+}	<0.1	[2]	<0.1	[2]	
Pb^+	<0.05	[2]	<0.05	[2]	
Mn^{2+}	<0.005	[2]	<0.05	[2] and [7]	
F^-	1.3	[7]	0.2	[7]	84.62
Cl^-	22780	[1]	16692	[1]	26.73
SO_4	3200	[1]	206	[1]	93.56
Ba^{2+}	<0.05	[7]	<0.05	[7]	
Sr^{3+}	9.5	[2]	0.2	[7]	97.89
Cu^{2+}	0.006	[2]	<0.025	[7]	
SiO_2	0.06	[2]	0.06	[7]	
Zn^{2+}	<0.05	[7]	<0.05		

(44046 mg/l), the nanofiltration system succeeded in removing 37% of feed TDS. The percentage removal for calcium and sulfate ions from feed water was 80.67% and 93.56% respectively. While for magnesium ions it was 88%. Also very high values for percentage removal were reached for bicarbonate ion — up to 64.06% from the nanofiltration system as can be seen in Table 1. Also the maximum sodium percentage removal achieved was 26.7%.

Fig. 1 summarizes the calculation of scaling potential of calcium carbonate scaling as given in Tables 2 and 3 for nanofiltration product water and seawater as a feed to MSF plants, at different conversion starting from 10% (CF 1.1) to 90%.

The % inhibition for calcium carbonate scaling as it was calculated from Stiff and Davis Saturation Index starting at 10% conversion (correction factor 1.1) is zero for Saudi seawater, that forced the operator to lower the natural pH of feed water to avoid calcium carbonate scaling even at a very

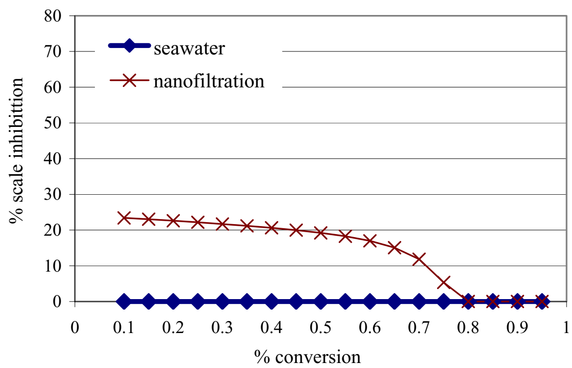

Fig. 1. Scaling potential for $CaCO_3$ with seawater and nanofiltration water feed before acidification.

Table 2
Calcium carbonate scaling potential for normal Saudi Arabia seawater at different conversions

y	k factor	p Ca	p alk	phs	R_b	pH brine	S&DSI	% inhibition
0.10	3.329	1.8750	2.6335	7.837296	38.76	7.8884	0.0511	0.00
0.15	3.357	1.8502	2.6092	7.816110	40.98	7.9126	0.0965	0.00
0.20	3.382	1.8239	2.5835	7.789462	43.49	7.9384	0.1489	0.00
0.25	3.403	1.7958	2.5560	7.755057	46.33	7.9658	0.2108	0.00
0.30	3.417	1.7659	2.5266	7.709483	49.57	7.9952	0.2857	0.00
0.35	3.419	1.7337	2.4950	7.647565	53.31	8.0268	0.3793	0.00
0.40	3.401	1.6989	2.4608	7.561247	57.68	8.0610	0.4998	0.00
0.45	3.353	1.6611	2.4236	7.437610	62.84	8.0982	0.6606	0.00
0.50	3.253	1.6198	2.3828	7.255159	69.03	8.1390	0.8839	0.00
0.55	3.065	1.5740	2.3376	6.976522	76.60	8.1842	1.2077	0.00
0.60	2.723	1.5228	2.2870	6.533040	86.06	8.2348	1.7018	0.00
0.65	2.095	1.4649	2.2296	5.789433	98.23	8.2922	2.5028	0.00
0.70	0.892	1.3979	2.1633	4.453552	114.44	8.3586	3.9050	0.00
0.75	0.000	1.3187	2.0847	3.403375	137.15	8.4372	5.0338	0.00
0.80	0.000	1.2218	1.9883	3.210134	171.21	8.5335	5.3234	0.00
0.85	0.000	1.0969	1.8640	2.960836	227.97	8.6579	5.6970	0.00
0.90	0.000	0.9208	1.6885	2.609234	341.51	8.8334	6.2242	0.00
0.95	0.000	0.6198	1.3880	2.007756	682.10	9.1338	7.1261	0.00

Table 3
Calcium carbonate scaling potential for nanofiltration product water as a result from Saudi experiments at different conversions

y	k factor	pCa	p alk	phs	R_b	pH brine	S&DSI	% inhibition
0.10	2.976	2.5887	3.0785	8.643193	2.09	6.6194	–2.0238	23.41
0.15	3.012	2.5639	3.0545	8.630112	2.20	6.6434	–1.9867	23.02
0.20	3.050	2.5375	3.0291	8.616840	2.34	6.6689	–1.9480	22.61
0.25	3.092	2.5095	3.0019	8.603175	2.49	6.6960	–1.9071	22.17
0.30	3.136	2.4795	2.9728	8.588759	2.66	6.7252	–1.8636	21.70
0.35	3.184	2.4474	2.9415	8.572976	2.86	6.7565	–1.8165	21.19
0.40	3.235	2.4126	2.9076	8.554752	3.09	6.7904	–1.7644	20.62
0.45	3.287	2.3748	2.8706	8.532206	3.37	6.8273	–1.7049	19.98
0.50	3.338	2.3334	2.8301	8.501955	3.70	6.8678	–1.6341	19.22
0.55	3.385	2.2877	2.7852	8.457737	4.10	6.9127	–1.5450	18.27
0.60	3.416	2.2365	2.7349	8.387430	4.60	6.9630	–1.4244	16.98
0.65	3.410	2.1785	2.6778	8.266180	5.25	7.0201	–1.2460	15.07
0.70	3.316	2.1116	2.6117	8.038828	6.11	7.0862	–0.9526	11.85
0.75	3.003	2.0324	2.5334	7.568844	7.32	7.1645	–0.4043	5.34
0.80	2.087	1.9355	2.4374	6.459965	9.13	7.2606	0.8006	0.00
0.85	0.000	1.8105	2.3133	4.123863	12.15	7.3846	3.2608	0.00
0.90	0.000	1.6344	2.1381	3.772558	18.19	7.5598	3.7873	0.00
0.95	0.000	1.4795	1.9837	3.463282	25.95	7.7142	4.2509	0.00

Table 4
Calcium sulfate scaling % inhibition for product water of nanofiltration and normal Saudi seawater at different proposed conversions

Con.	IP seawater	K_{sp} seawater	% inhibition	IP nanofiltration	K_{sp} nanofiltration	% inhibition
0.10	4.934E-04	1.566E-03	68.49%	6.141E-06	1.050E-03	99.42
0.15	5.531E-04	1.630E-03	66.07%	6.884E-06	1.092E-03	99.37
0.20	6.244E-04	1.702E-03	63.31%	7.772E-06	1.140E-03	99.32
0.25	7.104E-04	1.782E-03	60.13%	8.843E-06	1.192E-03	99.26
0.30	8.155E-04	1.872E-03	56.44%	1.015E-05	1.251E-03	99.19
0.35	9.458E-04	1.974E-03	52.10%	1.177E-05	1.318E-03	99.11
0.40	1.110E-03	2.092E-03	46.94%	1.382E-05	1.394E-03	99.01
0.45	1.321E-03	2.229E-03	40.72%	1.644E-05	1.483E-03	98.89
0.50	1.598E-03	2.390E-03	33.11%	1.990E-05	1.587E-03	98.75
0.55	1.973E-03	2.583E-03	23.60%	2.456E-05	1.711E-03	98.56
0.60	2.498E-03	2.821E-03	11.46%	3.109E-05	1.862E-03	98.33
0.65	3.262E-03	3.122E-03	0.00%	4.060E-05	2.052E-03	98.02
0.70	4.440E-03	3.517E-03	0.00%	5.527E-05	2.298E-03	97.60
0.75	6.394E-03	4.065E-03	0.00%	7.958E-05	2.634E-03	96.98
0.80	9.990E-03	4.891E-03	0.00%	1.243E-04	3.125E-03	96.02
0.85	1.776E-02	6.316E-03	0.00%	2.211E-04	3.931E-03	94.38
0.90	3.996E-02	9.581E-03	0.00%	4.974E-04	5.585E-03	91.09
0.95	1.598E-01	3.531E-02	0.00%	1.015E-03	7.969E-03	87.26

Table 5
Strontium sulfate scaling potential for product water of nanofiltration and normal Saudi seawater at different proposed conversions

Con.	IP seawater	K_{sp} seawater	% inhibition	IP nanofiltration	K_{sp} nanofiltration	% inhibition
0.10	4.46E-06	9.78E-06	54%	6.04E-09	6.49E-06	99.9
0.15	5.00E-06	1.02E-05	0.51	6.77E-09	6.76E-06	99.9
0.20	5.64E-06	1.07E-05	0.47	7.65E-09	7.06E-06	99.9
0.25	6.42E-06	1.12E-05	0.43	8.70E-09	7.39E-06	99.9
0.30	7.37E-06	1.17E-05	0.37	9.99E-09	7.77E-06	99.9
0.35	8.55E-06	1.24E-05	0.31	1.16E-08	8.20E-06	99.9
0.40	1.00E-05	1.32E-05	0.24	1.36E-08	8.68E-06	99.8
0.45	1.19E-05	1.40E-05	0.15	1.62E-08	9.25E-06	99.8
0.50	1.44E-05	1.51E-05	0.04	1.96E-08	9.92E-06	99.8
0.55	1.78E-05	1.63E-05	0.00	2.42E-08	1.07E-05	99.8
0.60	2.26E-05	1.79E-05	0.00	3.06E-08	1.17E-05	99.7
0.65	2.95E-05	1.98E-05	0.00	3.99E-08	1.29E-05	99.7
0.70	4.01E-05	2.24E-05	0.00	5.44E-08	1.45E-05	99.6
0.75	5.78E-05	2.60E-05	0.00	7.83E-08	1.67E-05	99.5
0.80	9.03E-05	3.15E-05	0.00	1.22E-07	1.99E-05	99.4
0.85	1.60E-04	4.09E-05	0.00	2.17E-07	2.51E-05	99.1
0.90	3.61E-04	6.27E-05	0.00	4.89E-07	3.60E-05	98.6
0.95	1.44E-03	2.39E-04	0.00	9.99E-07	5.19E-05	98.1

Table 6
Barium sulfate scaling potential for product water of nanofiltration and normal Saudi seawater at different proposed conversions

Con.	IP seawater	K_{sp} seawater	% inhibition	IP nanofiltration	K_{sp} nanofiltration	% inhibition
0.10	7.4837E-10	6.8139E-09	89.0	4.8176E-11	4.1541E-09	98.8
0.15	8.3900E-10	7.1640E-09	88.3	5.4011E-11	4.3637E-09	98.8
0.20	9.4716E-10	7.5562E-09	87.5	6.0973E-11	4.5981E-09	98.7
0.25	1.0777E-09	7.9990E-09	86.5	6.9374E-11	4.8621E-09	98.6
0.30	1.2371E-09	8.5031E-09	85.5	7.9638E-11	5.1618E-09	98.5
0.35	1.4347E-09	9.0827E-09	84.2	9.2362E-11	5.5054E-09	98.3
0.40	1.6838E-09	9.7569E-09	82.7	1.0840E-10	5.9036E-09	98.2
0.45	2.0039E-09	1.0552E-08	81.0	1.2900E-10	6.3711E-09	98.0
0.50	2.4247E-09	1.1504E-08	78.9	1.5609E-10	6.9285E-09	97.7
0.55	2.9935E-09	1.2669E-08	76.4	1.9271E-10	7.6056E-09	97.5
0.60	3.7886E-09	1.4128E-08	73.2	2.4389E-10	8.4475E-09	97.1
0.65	4.9484E-09	1.6017E-08	69.1	3.1855E-10	9.5256E-09	96.7
0.70	6.7353E-09	1.8566E-08	63.7	4.3359E-10	1.0961E-08	96.0
0.75	9.6989E-09	2.2217E-08	56.3	6.2436E-10	1.2976E-08	95.2
0.80	1.5154E-08	2.7934E-08	45.7	9.7557E-10	1.6037E-08	93.9
0.85	2.6941E-08	3.8339E-08	29.7	1.7343E-09	2.1313E-08	91.9
0.90	6.0618E-08	6.4240E-08	5.6	3.9023E-09	3.2920E-08	88.1
0.95	2.4247E-07	3.2311E-07	0.0	7.9638E-09	5.1134E-08	84.4

Table 7
Calcium fluoride scaling potential for nanofiltration product water and seawater at different conversions

y	IP_{CaF} Seawater	% inhibition Seawater	IP_{CaF} Nanofiltration	% inhibition Nanofiltration
0.10	7.7067E-11	0.00	3.5268E-13	99.12
0.15	9.1483E-11	0.00	4.1865E-13	98.95
0.20	1.0973E-10	0.00	5.0216E-13	98.74
0.25	1.3317E-10	0.00	6.0943E-13	98.48
0.30	1.6380E-10	0.00	7.4957E-13	98.13
0.35	2.0458E-10	0.00	9.3620E-13	97.66
0.40	2.6010E-10	0.00	1.1903E-12	97.02
0.45	3.3768E-10	0.00	1.5453E-12	96.14
0.50	4.4946E-10	0.00	2.0568E-12	94.86
0.55	6.1654E-10	0.00	2.8214E-12	92.95
0.60	8.7784E-10	0.00	4.0172E-12	89.96
0.65	1.3104E-09	0.00	5.9966E-12	85.01
0.70	2.0808E-09	0.00	9.5224E-12	76.19
0.75	3.5956E-09	0.00	1.6455E-11	58.86
0.80	7.0227E-09	0.00	3.2138E-11	19.66
0.85	1.6647E-08	0.00	7.6179E-11	0.00
0.90	5.6182E-08	0.00	2.5710E-10	0.00
0.95	4.4946E-07	0.00	7.4957E-10	0.00

Table 8
Scaling potential for silica with seawater and nanofiltration product water

Conversion, %	% inhibition (seawater)	% inhibition (NF product water)
0.10	99.96	99.92
0.15	99.95	99.92
0.20	99.95	99.92
0.25	99.95	99.92
0.30	99.95	99.91
0.35	99.94	99.91
0.40	99.94	99.90
0.45	99.94	99.90
0.50	99.93	99.89
0.55	99.93	99.88
0.60	99.92	99.87
0.65	99.91	99.86
0.70	99.90	99.84
0.75	99.89	99.82
0.80	99.87	99.78
0.85	99.84	99.73
0.90	99.78	99.64
0.95	99.64	99.54

low correction factor and low TDS that are employed using acid treatment or using antiscalant to avoid the calcium carbonate scaling. Table 3 or Fig. 1 for calcium carbonate scaling potential using nanofiltration product water as a feed to MSF show the result of 23.4% natural inhibition without changing the natural pH or using antiscalant. Although the conversion has been increased and the inhibition percentage has been decreased. But the inhibition percentage is still of about 19% at 0.5% conversion (CF 1.82) as shown in Fig. 1. We can see that the use of a nanofiltration membrane results in an incredible scaling inhibition that has been never achieved by any other treatment method. Also in Figs. 2–6 the percentage inhibition for calcium sulfate scaling, barium sulfate and strontium sulfate were almost reaching 100% at 10% conversion, and even at 90% conversion the inhibition percentage is still in very high compared to scaling potential for normal seawater, although 90% conversion results in a high degree of saturation and highly concentrated

Table 9
The $CaCO_3$ scaling potential after acidification at different proposed pH using the nanofiltration product water at different conversions

% inhibition *y*	pH after acid 6.51	pH after acid 6.45	pH after acid 6.36	pH after acid 6.30	pH after acid 6.06	pH after acid 5.66
0.10	25.46	26.69	26.81	28.10	33.80	43.92
0.15	25.44	25.60	26.82	28.12	33.88	44.16
0.20	25.42	24.95	26.82	28.13	33.97	44.42
0.25	25.40	24.90	26.82	28.15	34.05	44.69
0.30	25.37	24.88	26.82	28.16	34.13	44.97
0.35	25.33	24.85	26.81	28.16	34.21	45.27
0.40	25.27	24.80	26.78	28.15	34.28	45.57
0.45	25.17	24.71	26.72	28.10	34.31	45.88
0.50	25.01	24.55	26.59	27.99	34.30	46.16
0.55	24.72	24.28	26.34	27.77	34.19	46.40
0.60	24.21	23.76	25.87	27.32	33.89	46.52
0.65	23.22	22.77	24.93	26.43	33.19	46.39
0.70	21.18	20.73	22.98	24.54	31.64	45.67
0.75	16.48	15.98	18.43	20.13	27.86	43.41
0.80	2.53	1.85	4.87	6.96	16.51	35.91
0.85	0.00	0.00	0.00	0.00	0.00	8.05
0.90	0.00	0.00	0.00	0.00	0.00	3.61
0.95	0.00	0.00	0.00	0.00	0.00	0.00

stream feed. The nanofiltration membrane succeeded in preventing all types of scaling even at high percentage conversion.

With normal seawater the scaling potential for calcium sulphate (Fig. 2) started from about 70% and decreased to zero at 60% conversion, while for nanofiltration product as a makeup feed the % inhibition was almost 100% in spite of the high percentage conversion or concentration factor. The same was noticed for strontium sulphate where it was only 50% at 10% conversion and decreased to zero at 50% conversion, whereas for nanofiltration it was constant almost at 100% inhibition. Fig. 6 shows that % inhibition for seawater is zero even at 10% conversion but with nanofiltration this inhibition increased to 100% and decreased to 85% at 65% conversion.

9. After acidification process

Fig. 7 shows the differences of calcium carbonate scaling potential at different proposed feed pH after acidification process. The pH of feed water was changed by addition of acid to reduce the feed pH to the desired pH, at which there is no risk for calcium carbonate scaling, since the pH of feed water decreases as the % inhibition increases.

Starting from pH equal to 6.5, since the original pH of nanofiltration product water is 7.85, the % inhibition for nanofiltration product water increased from 25.46% at pH 6.5 to almost 43.92% (Fig. 7) at pH 5.66. The % inhibitions are close to zero at almost 85% conversions. As the feed pH values decreased the % inhibition increased, but

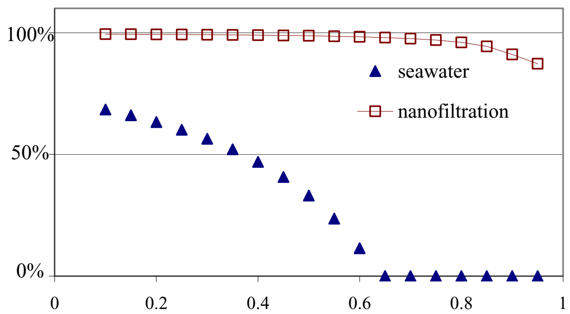

Fig. 2. Scaling potential for $CaSO_4$ with seawater and nanofiltration water feed.

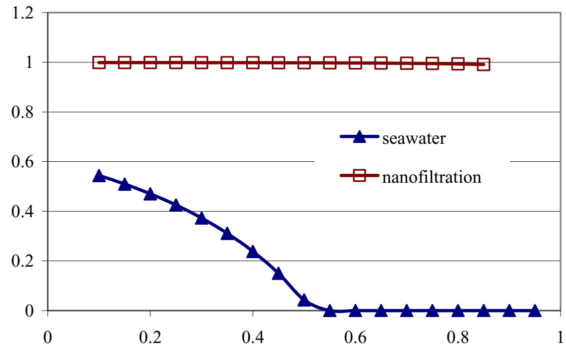

Fig. 3. Scaling potential for $SrSO_4$ for different feed waters.

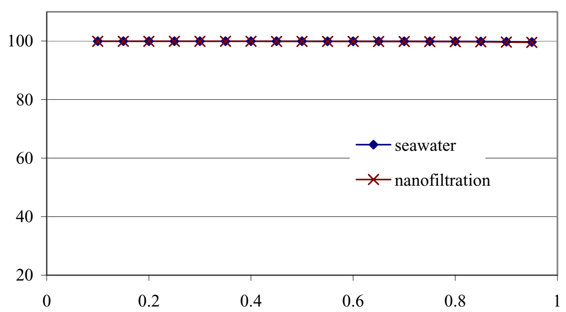

Fig. 4. Scaling potential for silica with different feed waters.

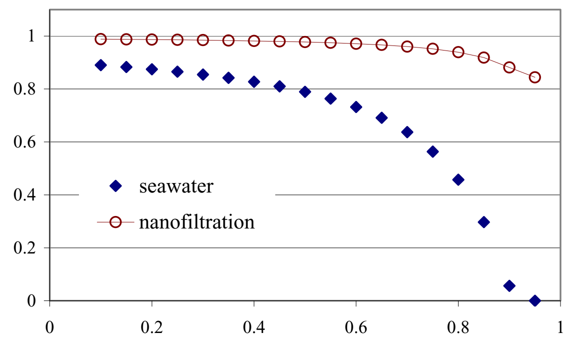

Fig. 5. Scaling potential for $BaSO_4$ with seawater and nanofiltration water feed.

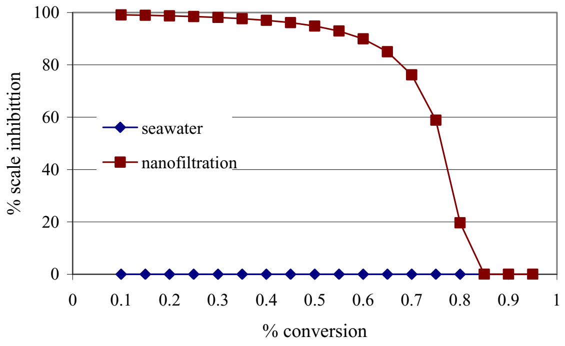

Fig. 6. Scaling potential for CaF with different feed waters.

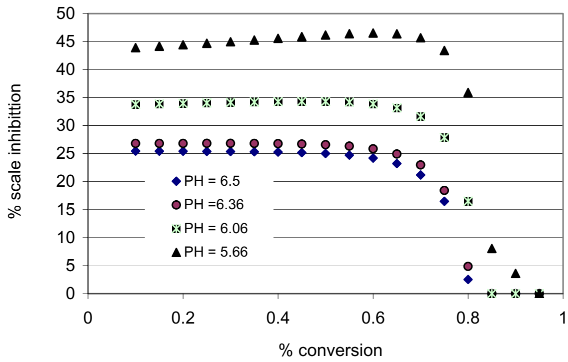

Fig. 7. The scaling potential for $CaCO_3$ at different proposed pH after acidification for a nanofiltration product water.

the low PH value will result of increasing corrosion risk. The % inhibitions decreases also as the conversion increases. All these calculations prove the reliability of the nanofiltration product water as a makeup for MSF, even without acid treatment and without any antiscalant, since there is no risk for scaling as calculated in this paper and proved by Saudi experiments.

10. Conclusions and recommendations

- The product water from nanofiltration system can be considered as a revolution in scale prevention technique. It guarantees that the plants operating on such type of water will not suffer from any type of scaling, the risk of calcium sulfate scaling is totally eliminated by this technique to almost 100%.
- This membrane if applied in a MSF plant will allow operation at high operating temperature, more benefits, more production, and more savings will be gained from such operating mode and even calcium carbonate scale will not need any type of treatment.
- When comparing nanofiltration and normal seawater, its strongly recommended to use nanofiltration product water to operate a plant at high temperature even without any types of chemicals to prevent scaling. Nanofiltration proves its reliability even when a very concentrated stream is used.
- There are many different types of nanofiltration membranes. Best suitable membranes must be chosen based on real operation and scaling calculation.
- This study only concerns the chemical composition and scaling potential, but still there are a lot of operation parameters. Cost has to be studied to decide if nanofiltration is suitable for Gulf MSF plants or not, which requires further study.

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