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Scale control in multistage flash (MSF) desalination plants – lessons learnt

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ABSTRACT

Adoption of successful methods for scale control is one of the main factors that contributed to the wide application of the multistage flash (MSF) desalination processes in the Gulf Cooperation Council (GCC) regions. Formation of scale is mainly caused by crystallization of calcium carbonate and magnesium hydroxide (alkaline scale) and calcium sulfate (non-alkaline scale). In this paper, the evolution of alkaline scale control in MSF desalination plants during the last four decades is described and reviewed. The unique experience gained by the Saline Water Conversion Corporation (SWCC) of Saudi Arabia in controlling alkaline scale formation is presented. The extensive optimization tests, which have been carried out by SWCC and materialized in significant reduction of antiscalant dose rates are highlighted. Procedures employed for online sponge ball cleaning are discussed. Various corrective measures that are normally adopted to mitigate the consequences of malfunctions of antiscalant dosing or the online ball cleaning systems are reviewed. Prospects of controlling non-alkaline scale and operating MSF desalination plants at high top brine temperature (TBT) using nanofiltration pretreatment are discussed. Increase of TBT shall result in the increase of water production and reduction of specific energy consumption.

Keywords: MSF; Scale control; Alkaline scale; Ball cleaning; Nanofiltration pretreatment

1. Introduction

Control of scale formation on heat transfer surfaces is one of the basic problems in thermal desalination processes. Formation of scale on heat transfer surfaces impedes the rate of heat conductance and increasing energy consumption. The main scale forming constituents of seawater are calcium bicarbonate, magnesium salts and calcium sulfate. When the temperature of a saline solution rises above about 65°C, bicarbonate ion tends to disassociate, producing carbon dioxide, water and a carbonate ion [1]. Carbonate ions combine with calcium ions to form soluble calcium carbonate that precipitates. As heating continues and temperature increases above 75°C, any remaining carbonate ions react with water to form more carbon dioxide and hydroxyl ions. These hydroxyl ions combine with magnesium to form magnesium hydroxide. Calcium carbonate and magnesium hydroxide are generally referred to as "alkaline scales." Formation of alkaline scale is controlled by either lowering pH through bicarbonate depletion or by threshold additive chelation.

Non-alkaline scale consists mainly of calcium sulfate compounds and is normally formed at relatively high concentration factors (1.8–2.0) and temperatures above 110°C–120°C. The major scales that crystallize are: anhydrite calcium sulfate ($CaSO_4$), hemihydrate calcium sulfate ($CaSO_4.½H_2O$) and dihydrate calcium sulfate ($CaSO_4.2H_2O$). The formation of non-alkaline scales is dependent on temperature and saline solutions concentrations. The anhydrite calcium sulfate solubility is always exceeded in practice but scale formation may not happen since a long period is needed before anhydrite deposits from supersaturated solutions. The solubility of calcium sulfate hemihydrate can vary from about 2,240 ppm at a concentration factor of 1°C and 150°C to 6,800 ppm at a concentration factor of 3.5°C and 94°C. A normal multistage flash (MSF) evaporator thus operates under conditions where the brine is supersaturated with respect to anhydrite but normally below the hemihydrate solubility. Formation of non-alkaline scale is primarily controlled, so far in commercial plants, by operating at top brine temperatures

(TBTs) that are lower than its appreciable precipitation limits, that is, TBT < 120°C in view of the raised salt concentration in MSF brine streams.

Alkaline scale formation in condenser tubes is a major problem encountered in the operation of MSF distillers. Prevention of scale deposition can be controlled by removal of carbonate through pH adjustment using acid addition or by controlling scale precipitation through the addition of decrystallizing threshold agents that are mainly organic polymer compounds. The commonly used antiscalants are derived from three families: condensed polyphosphates, organophosphonate and polyelectrolytes. Polyelectrolytes are mostly polycarboxylates which include polyacrylic acid, polymethacrylic acid and polymaleic acid (PMA).

The mechanism of threshold agents has not yet been fully established. It might be due to adsorption of threshold agents on the scale crystal nuclei which leads to crystal distortion and subsequent formation inhibition [1]. Mixtures of sodium tripolyphosphate dispersing agent have been used to inhibit alkaline scale deposition in seawater evaporators since 1950s [2]. The major problem with polyphosphate-based inhibitors was found to be the thermal degradation of polyphosphate at temperatures above 90°C and the subsequent loss of threshold effect of the product. This restriction in TBT to 90°C (by hydrolysis) limited the thermal efficiency of evaporator designed for threshold treatment [2,3].

Acid dosing was introduced in 1960s as a means of overcoming the temperature limitations and the poor performance of polyphosphate [1]. Acid dosing, by removing the bicarbonate from the feedwater, allowed evaporators to operate at increased top temperatures, close to the calcium sulfate solubility limits. It was found to have certain drawbacks such as the mandatory careful control and monitoring of the dose level which was quite essential to minimize the risks of plants' corrosion or scale formation and to ensure a reasonable plant life.

As problems associated with acid operation became dominant, the opportunity for high temperature scale control additives to replace acid while giving commensurable performance was noted from the mid of 1970 onwards [1,2]. Low molecular weight polymeric/carboxylic acid and phosphorous base alkaline were developed as high temperature additives. Phosphonate-based polymers do not hydrolyze as easily as the polyphosphate group due to the greater stability of the C–P bond in phosphonates as compared with the P–O bond in phosphates.

The dosing rate of antiscalant is one of the most important operating parameters. Underdosing leads to scale formation, while overdosing is believed to enhance sludge formation [3]. It is thus essential to establish an optimum dose rate.

Although, a number of methods have been developed to minimize or prevent the formation of alkaline scales, no commonly accepted method for avoiding the formation of scales due to calcium sulfate salts at high temperatures and brine concentrations in large commercial MSF plants is available. The only commercialized approach so far (i.e., currently used to prevent the formation of calcium sulphate) is to operate the plant below the precipitation limits of calcium sulfate.

In this paper, the evolution of alkaline scale control in MSF desalination plants and lessons learnt during the last four decades are described and reviewed. The prospects of controlling non-alkaline scale and operating MSF desalination plants at high TBT using nanofiltration (NF) pretreatment are also discussed.

2. SWCC's experiences on scale control

Saline Water Conversion Corporation (SWCC) of Saudi Arabia has been actively involved in the inhibition of scale formation in order to improve performance of its distillers. A number of optimization tests have been carried out resulting in successful operation of MSF distillers at low antiscalant dosing rates [4–17]. This can be attributed to several factors such as plant operators' awareness to reduce chemical dosing while maintaining effective plant performance, adoption of online sponge ball cleaning and competition among various additive suppliers to provide the most cost-effective dose levels to meet the needs of SWCC.

Gained operational experiences on Al-Khobar Phase II plant during the period 1982–1992 was reported [7]. Water production, TBT, antiscalant type and dose rate and performance ratio of three distillers were reported. Distillers were initially dosed with polyphosphate antiscalant for a period of 1 year (1984) and with a TBT of 85°C and a dose rate of 3 ppm. Polyphosphate was then replaced by PMA during the year 1985 with a dose rate of 2 ppm and TBT of 90°C. From 1986 up to 1992, polyphosphonate (PPN) liquid with a reasonably low dose rate (around 1 ppm) and TBT ranging between 85°C and 100°C was used. Up to 1990, the gain out ratio (GOR) ranging between 6.6 and 7.0 was near or better than the design value. From 1990 onwards the GOR dropped to as low as 6.3 which was mainly attributed to postponed acid cleaning. It has been concluded that reasonably low antiscalant dose rate (1–2 ppm of makeup seawater) was adequate, ideal TBT for operation with proven capabilities of PMA was 105°C and no safe operation could be endorsed without good sponge ball cleaning. Close monitoring of the MSF distiller would mandate acid cleaning of heat transfer tubes once or as a maximum twice per decade.

A direct comparison on performance characteristics and economics of three additives tested on the MSF distillers of Al-Jubail Phase I has been reported [4]. The tested additives include polyphosphate, PPN and polycarboxylates. Performance testing revealed that the best scale control method was operation at low temperature (90.6°C) and low additive dosing. The three tested antiscalants proved to be successful during a 30 d test period. Individual dose rates varied between 3 and 5 ppm. The sponge rubber ball online cleaning system was found to be effective with polyphosphate additive. However, the slight soft scale accumulation with polycarboxylate and PPN additives did not warrant extensive use of the ball cleaning system. The design heat transfer fouling resistance was more than required by either type of chemical additive. If a lower design fouling factor (FF) is used, smaller heat transfer area will be required which will have a significant decrease in total evaporator installed equipment cost.

Another study was reported on the evaluation of various additives at Al-Jubail Phase I during reliability tests [5].

Performance ratio calculations were used to predict the time span between acid cleaning for three additives. Assuming a linear relationship between performance ratio and time, test results showed that the predicted time spans in days before acid cleaning is required were 310, 590 and 1,466 for three additives tested. It has been stated that it would be of great interest if chemical instruments could be fixed on the MSF distillers to measure in site both acid and alkalinity under operating conditions. Such measurements will give a direct estimate of the quantity of scale deposited.

Optimization of scale control additive dose levels at different TBTs in Al-Khobar II and Al-Jubail II desalination plants has been reported [6]. Both plants were originally designed to operate at low or high temperature using polyphosphates or liquid polymers. Suggested dose rates by design were from 3 to 5 ppm for low temperature additives and 7 to 12 ppm for high temperature additives. Antiscalant dose rates were reduced in a stepwise procedure. Dose levels were reduced to as low as 2.2 and 0.8 ppm for effective and safe operation at high and low temperature, respectively.

Trial tests on the performance of PMA and PPN antiscalants at Al-Jubail Phase II desalination plant was reported [8]. Results revealed that PMA performed better compared with PPN. Also, visual inspection for selected units after a predetermined time span revealed that PMA had a better performance. However, the ball cleaning operation had more tangible effect on the PPN group over the polymaleic group.

Evaluation test was carried out in one of Al-Jubail Phase II distillers to investigate the effectiveness of phosphonic acid-based antiscalant at a TBT of 90.6°C and dose rate of 0.8 ppm [14]. Thermal and chemical parameter monitoring of the distiller which included flash range, performance ratio, overall heat transfer coefficient, FF, loss of total alkalinity as well as distillate production and conductivity during a test period of 337 d showed smooth and steady operation. Also, post-test visual inspection of the unit revealed that heat transfer tubes of the brine heater were clean and demister pads relatively clean with no detrimental scale built up. It has thus been concluded that the antiscalant was effective and successful in controlling scale formation at a TBT of 90.6°C and dose rate of 0.8 ppm.

A trial test was conducted in Unit 6 of Al-Jubail Plant Phase II at a TBT of 98°C and dose rate of 0.8 ppm of PMA-based antiscalant for a period of 394 d [17]. Thermal performance and chemical assessment of the unit showed that operation during test period was smooth and steady. The FFs of both brine heater and heat recovery section were found well below corresponding design values. Monitoring of loss of total alkalinity (LTA) indicated no scale deposition. Post-test visual inspection of distiller revealed that brine heater, flash chamber and water boxes were in good condition with no adverse effects due to low dose rate of antiscalant. It has thus been concluded that PMA-based antiscalant was quite effective and successful in controlling scale formation at a TBT of 98°C and a dose rate of 0.8 ppm for a test period of 394 d.

A comprehensive study was carried out [16] for direct comparison of the performances and effectiveness of three of the most widely used antiscalants by SWCC which included two different maleic acid-based copolymer antiscalants, and one phosphonate-based antiscalant. The comparative study was performed in a MSF pilot plant under harsh operating

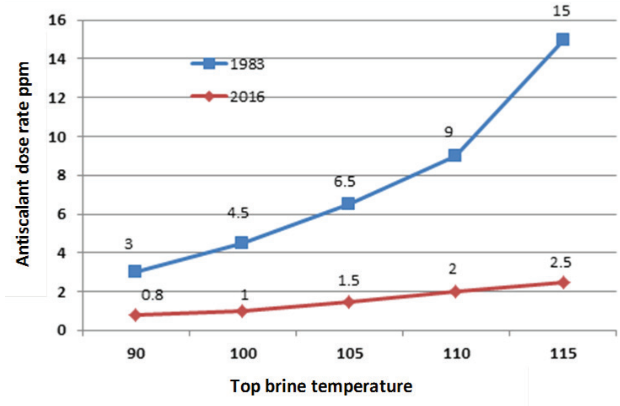

Fig. 1. Achievements of SWCC in controlling alkaline scale formation.

conditions. For each of the three antiscalants, a MSF pilot plant was operated at a TBT of 119°C, dose rate of 1 ppm and brine recycle concentration factor of 1.9 for 1 month. A baseline test was performed under the same TBT and concentration factor and without the use of antiscalant. The rate of increase of brine heater FF with time was observed and quantified using regression analysis. The test results revealed that the three examined antiscalants were effective in suppressing scale formation under harsh selected operating conditions. However, a maleic acid-based copolymer antiscalant (2) was the best performing material followed by a maleic acid-based copolymer antiscalant (1) and phosphonate-based antiscalant (3), respectively. Because of excellent scale control effectiveness of the three examined chemical additives under MSF pilot plant harsh operating conditions, it is recommended to reconsider current scale control method of commercial MSF plants with regards to optimization of antiscalant dosing rates and brine concentration factors.

As shown in Fig. 1, the optimization tests which were carried out by SWCC, resulted in reduction of antiscalant dose rates from 3.0 ppm as recommended by the plant manufacturers (in 1983) to 0.8 ppm at TBT of 90°C and from 9.0 to 2.0 ppm at TBT of 110°C.

3. Scale control and on-load sponge ball cleaning

Although, the formation of scale is combated and controlled by threshold treatment with the use of antiscalant, its complete prevention is impracticable. Sludge or distorted scale is also formed as a result of threshold treatment deposited on tube metallic surfaces and induce resistance to heat transfer. The combined use of chemical additives and online tube cleaning has been proved to be the most cost-effective means to combat scale formation and to avoid acid cleaning [18–20].

All SWCC MSF plants are employing on-load sponge ball cleaning. The chemical treatment, ball to tube ratio and frequency of cleaning in different MSF plants are shown in Table 1. The ball to tube ratio for plants using chemical additive treatment varies from as low as 0.22 in Al-Shuqaiq up to about 0.45 in Al-Jubail Phase I and Al-Khobar plants with average frequency of three ball cleaning operations per day. The ball to tube ratio in SWCC MSF plants, thus in most cases, lie within the reported accepted range [18,19]. Larger

Table 1
On-load sponge ball cleaning

S. No.	Plant	Chemical treatment	Ball/tube ratio		Frequency of ball cleaning operation	No. of cycles per operation
			BH	HRC		
1	Al-Jubail Phase I	Antiscalant	0.450	0.427	3 operations/d	8 cycles/operation
2	Al-Jubail Phase II					
	C2 and C3	Antiscalant	0.342	0.324	3 operations/d	8 cycles/operation
	C4	Antiscalant	0.270	0.257	3 operations/d	8 cycles/operation
	C5	Antiscalant	0.300	0.302	3 operations/d	8 cycles/operation
3	Jeddah Phase II	Acid	0.296	0.236	1/week	3 cycle/operation
4	Jeddah Phase III	Antiscalant	0.29	0.665	3 operations/d	4 cycles/operation
5	Jeddah Phase IV	Antiscalant	0.251	0.370	2 operations/week	10 cycles/operation
6	Al-Khobar II	Antiscalant	0.453	0.458	3 operations/d	9 cycles/operation
7	Yanbu I	Antiscalant	0.243	0.249	3 operations/d	12 cycles/operation
		Acid	0.243	0.249	1 operations/week	12 cycles/operation
8	Al-Shuqaiq	Antiscalant	0.22	0.22	3 operations/d	8 cycles/operation (16 for high TBT)
9	Al-Shoaiba I	Antiscalant	0.251	0.253	3 operations/d	3 cycles/operations
10	Al-Khafji	Antiscalant	0.351	0.351	1 operations/d	9 cycles/operation

BH, Brine Heater; HRC, Heat Recovery.

number of ball to tube ratio may cause problems by several balls passing one tube simultaneously and getting stuck while smaller ratio is not capable to reach all tubes [20]. The wide variation of ball to tube ratio reveals that ball cleaning operation is not yet well established. This can be attributed to its dependence on many interacting operating and design factors such as brine chemistry, type of inhibitor and control regime, ball type and MSF design parameters such as temperatures, number of stages and tube length, flow pattern and arrangement of ball injection points.

4. Interruption of antiscalant dosing or circulation of cleaning balls

Commercial MSF desalination plants sometimes experience interruption of antiscalant dosing or circulation of cleaning balls. Either the interruption may be due to sudden system failure or the system isolation for maintenance work. In such circumstances, commercial plants normally adopt certain operating procedures to counter consequences of maloperation of antiscalant dosing or cleaning balls systems.

Corrective measures that are normally adopted by SWCC MSF plants to mitigate the malfunction consequences of antiscalant dose or the online ball cleaning systems are varying [21,22]. Generally, there are three different approaches normally followed by SWCC MSF plants to counter interruption and failure of an antiscalant dosing system. Al-Khafji, Al-Shoaiba and Yanbu plants generally resort to distiller shut downs immediately or employing a cold circulation mode. The second group of plants, which include Al-Jubail, Al-Khobar and Al-Shuqaiq, utilize continuous circulation of cleaning balls and reduction of the TBT to less than 90°C. Jeddah plants, which represent the third approach, use a standby acid dosing system when the antiscalant dosing system malfunctions.

An evaluation study was carried out to determine the impact of interruption of antiscalant dosing at Al-Khobar Phase II plant. The evaluation test revealed that it is safe to operate the MSF distiller without antiscalant dosing for a maximum period of 3 h [21].

Remedial actions, which are normally followed by SWCC MSF plant when the ball cleaning system is inoperative, are also quite different. Al-Jubail plant prefers to solely increase the antiscalant dose rate by 50%. Other plants favor the increase of antiscalant dose rate coupled either with the increase of the makeup flow such as Al-Khobar or Al-Khafji plants or with the reduction of the distiller production load as normally practiced in Yanbu plant. Jeddah plants can tolerate operation without ball cleaning for a maximum period of 1 month when using phosphonate-based antiscalant and 6 months with the use of polycarboxylate-based antiscalant.

5. Economic impact of effective and optimized MSF scale control

The extensive series of optimization tests which were carried out in various SWCC plants resulted in a substantial decrease in the antiscalant dosing rates, which, in turn, reduced the operational costs of the desalination plants. The tests resulted in reduction of antiscalant dosing rates from 1.0 to 0.8 ppm at TBT of 90°C and from 2.5 to 1.8 ppm at TBT of 110°C. For example, the annual savings due to the reduction of antiscalant dose rate to 0.8 ppm at TBT of 90°C and 98°C in Al-Jubail Phase I and II MSF desalination plants are around 4.5 million Saudi Riyals (SR). For Jeddah distillers, which operate at TBT of around 110°C, a reduction in dose rate to 1.8 ppm at the Jeddah IV plant and 2.5 ppm at the Jeddah III plant resulted in annual savings of more than 1.5 million SR. The total annual savings due to reduction of antiscalant dose rates in SWCC MSF plants is more than 12 million SR.

As a result of limited operational experience, it has been observed that high design FFs were initially selected for MSF plants which were built two or three decades ago. The design FFs of the brine heaters and heat recovery sections for additive plants range between 0.176 and 0.325 m^2K/kW. However, due to the good performance of antiscalants in conjunction with the effective use of sponge ball cleaning, these FF values are very conservative (larger than required). Selection of large FFs result in the design of heat exchangers with more surface area than required. Low values of design FFs such as 0.15 m^2K/kW, or even lower can be safely employed in new additive MSF designs [15].

However, selection of high design FFs for existing MSF plants resulted in oversizing of the heat transfer surfaces. This will allow these plants to operate at a TBT equal to or even higher than maximum design values. The result is an increase in water production.

6. Potential of development of non-alkaline scale control

$CaSO_4$ formation is primarily controlled, so far in commercial plants, by operating at TBTs lower than its appreciable precipitation limits (TBT < 120°C in view of the raised salt concentration in MSF brine recycle stream). The Saline Water Desalination Research Institute (SWDRI) of SWCC of Saudi Arabia recently introduced a promising approach for pretreatment of seawater using NF membrane [23–31]. Chemical analysis of the NF membrane permeate showed that the total hardness as $CaCO_3$ in seawater is reduced from 7,857 to 510 ppm, sulfate ions from 3,400 to less than 1 ppm and the bicarbonate ions which were initially reduced by acid addition from 158 to 123 ppm to protect the NF membranes, were reduced further by NF membrane to 35 ppm. The pretreated seawater can thus be used as makeup to MSF and will subsequently offer a viable alternative to escape from the TBT limitation. Removing calcium, magnesium, bicarbonate and sulfate ions from the raw seawater by NF opens the possibility to safely increase TBT of MSF distiller above 120°C. Increase of TBT of MSF plants will result in the decrease of specific thermal and electrical energy consumption as well as reduce the required specific heat transfer area and will subsequently reduce unit water production cost [27,30,31].

Extensive experimental tests were carried out on a pilot plant scale with 24 m^3/d water production capacity to explore the potential of using NF pretreatment to the MSF process [32,33]. The MSF was first operated within the context of the dihybrid NF/MSF configuration at TBT up to 130°C, which is the design TBT limit of the MSF pilot plant [32]. The thermal performance of the unit during an operational period of 50 d was smooth and FF of the brine heater was steady and well below the design FF. The product recovery of the MSF unit was increased up to 73% as compared with only 40% at TBT of 90°C when the makeup feed consisted of seawater without NF pretreatment [32]. Post-test visual inspection revealed that the brine heater was in very clean condition and there was no sign of scale or sludge deposition on heat exchanger surfaces. Chemical analysis revealed that concentration of sulfate and calcium ions in the brine recycle were well below the solubility limit of calcium sulfate salt. It has been concluded that the MSF pilot plant using NF product could be operated safely without any scaling problems up to a TBT of 130°C.

Extensive experimental studies were also conducted when the MSF pilot plant was operated within the context of the trihybrid NF/RO/MSF configurations shown in Fig. 2 [33]. The system was configured in such a way that the NF unit received seawater feed from the heat rejection of the MSF pilot plant and was able to operate at a fairly constant temperature of about 33°C which produced NF permeate (NFP) at a recovery ratio of about 64%. The sea water reverse osmosis (SWRO) unit which received the NFP as a feed yielded a permeate recovery of about 47%. Average chemical analysis of the reverse osmosis (RO) reject revealed that the sulfate and calcium concentrations were only 124 and 281 ppm, respectively, and was subsequently used as a makeup to the MSF pilot plant. The very low concentration of the sulfate and calcium ions in the brine recycle that were below the saturation limits enabled MSF unit to operate safely up to a TBT of 130°C (unit temperature design limit) and water recovery ratio of 69%.

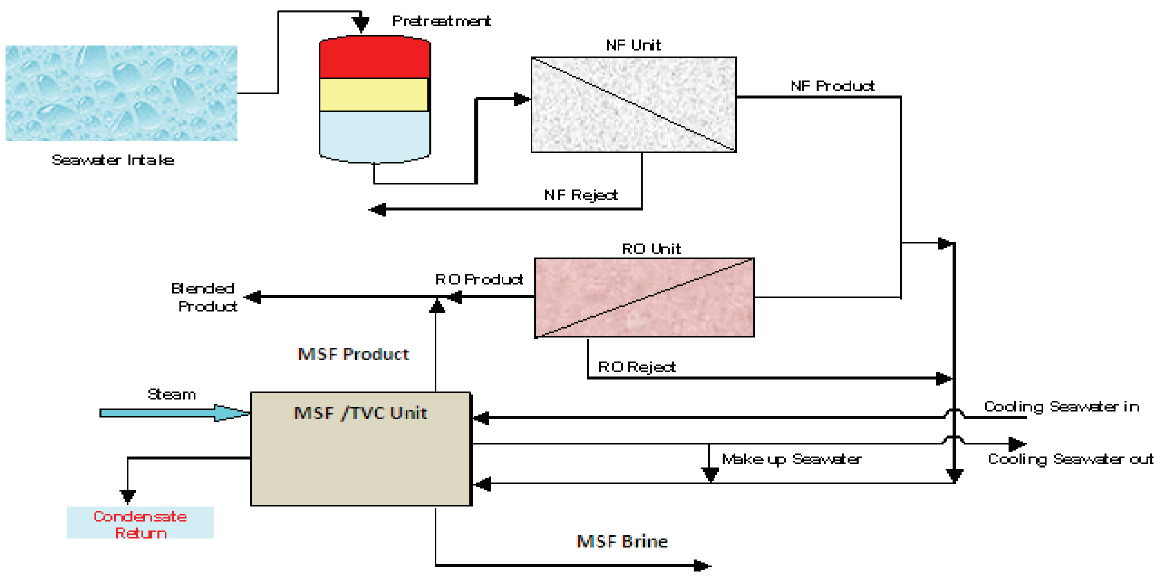

Fig. 2. Schematic diagram of the trihybrid NF/RO/MSF desalination system.

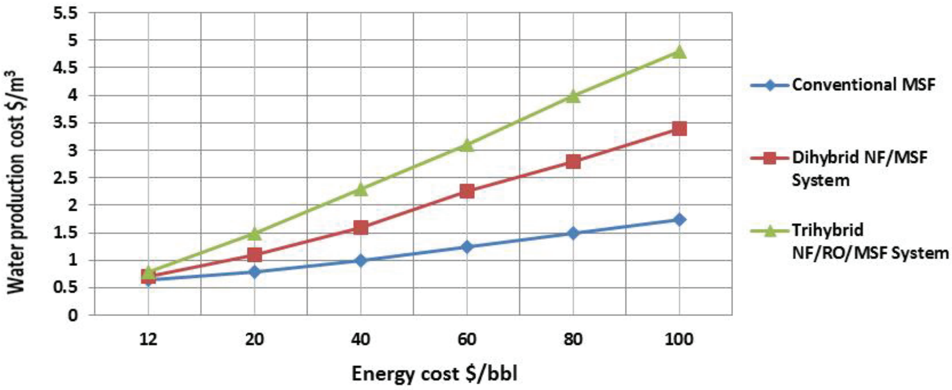

Fig. 3. The impact of energy cost on water production cost.

Based on pilot plant experimental results, the economic feasibility of operating a MSF unit at elevated TBT reaching 130°C using a dihybrid NF/MSF or trihybrid NF/RO/MSF configuration, was examined. Fig. 3 shows the impact of energy cost in $/bbl oil equivalent on the water production costs for the three different cases:

Case 1: MSF plant operating at TBT of 110°C with conventional scale control additives.
Case 2: MSF unit operating within the context of dihybrid NF/MSF configuration.
Case 3: MSF unit operating within the context of trihybrid NF/RO/MSF configuration.

Fig. 3 shows the trihybrid NF/RO/MSF configuration consistently yields low water production cost compared with dihybrid NF/MSF and conventional MSF processes. The percentage reduction in water production cost of the trihybrid NF/RO/MSF system compared with single MSF unit ranges from 24% to 63% as the energy costs varies from $12/bbl to $100/bbl. Meanwhile, the percentage reduction of water production costs of the dihybrid NF/MSF system ranges between 12% and 30% for the same range of energy costs.

NF pretreatment concept has so far been only applied in a commercial scale, by being integrated with one of the production lines of an existing SWRO desalination plant in Saudi Arabia [34]. Application of NF pretreatment resulted in increasing SWRO water production by 42%. NF pretreatment is not feasible to be integrated with existing MSF plants which are mainly designed to operate at TBT up to 110°C. At such TBT range, addition of chemical additives (antiscalants) is quite effective for scale control. Trihybrid NF/RO/MSF concept is technically feasible for only newly built desalination plants.

7. Conclusion

Procedures which are normally employed for scale control and contributed to the massive application of MSF desalination plants in the GCC regions are reviewed. The majority of MSF desalination plants are currently employing high temperature inorganic or organic polymers rather than acids to control the formation of alkaline scales. Antiscalant dose rates are optimized to as low as 2.0 and 0.8 ppm at TBT of 110°C and 90°C, respectively. In combination with chemical additives, MSF plants are employing online ball tube cleaning for ball to tube ratios ranging from 0.22 to 0.45 to combat scale formation. As a result of effective additive scale control and ball cleaning systems, optimized design FFs less than 0.15 m^2K/kW can be safely employed in future additive MSF designs. Various corrective measures normally adopted by MSF plants to mitigate the consequences of malfunctions of the antiscalant dosing online ball cleaning systems are reviewed. It is also found that NF pretreatment is a promising approach to control non-alkaline scale in MSF desalination plants.

References

[1] A.M.S. El Din, R.A. Mohammed, Brine and scale chemistry in MSF distillers, Desalination, 99 (1994) 73–111.
[2] M.A. Finan, S. Smith, C.K. Evans, J.W.H. Muir, Belgard EV-15 Years of Experience in Scale Control, Proc. 4th World Congress on Desalination and Water Reuse, 1989, pp. 341–357.
[3] M.A. Al-Sofi, S. Khalaf, A. Al-Omran, Practical experience in scale control, Desalination, 73 (1989) 313–325.
[4] A.M.A. Al-Mudaiheem, R.M. Szostack, Evaluation of Chemical Additives for Scale Control in MSF Evaporators, Topics in Desalination, SWCC, Saudi Arabia, Vol. 8, 1986.
[5] N. Nada, Evaluation of Various Additives at Al-Jubail Phase-I During Reliability Trials, Topics in Desalination, SWCC, Saudi Arabia, Vol. 13, 1986.
[6] M.A. Al-Sofi, M.A. Al-Hussain, S. Al-Zahrani, Additive scale control optimization and operation modes, Desalination, 66 (1987) 11–32.
[7] M.A. Al-Sofi, M.A. Al-Hussain, A.A. Al-Omran, K.M. Farran, A full decade of operating experience on Al-Khobar II multistage flash (MSF) evaporators (1982–1992), Desalination, 96 (1994) 313–323.
[8] S. Al-Zahrani, A.M. Al-Ajlan, A.M. Al-Jardan, Using Different Types of Antiscalants at the Al-Jubail Power and Desalination Plant in Saudi Arabia, Proc. IDA and WRPC World Conference on Desalination and Water Treatment, Yokohama, Japan, Vol. I, 1993, pp. 421–431.
[9] M.A.K. Al-Sofi, E.F. El-Sayed, M. Imam, G.M. Mustafa, T. Hamada, Y. Tanaka, S. Haseba, T. Goto, Heat Transfer Measurements as a Criterion for Performance Evaluation of Scale Inhibitor in MSF Plants, Proc. 7th IDA International Conferences, UAE, 1995.
[10] A.H. Osman, M.A.K. Al-Sofi, G.M. Mustafa, A.G.I. Dalvi, The Performance of Different Antiscalants in Multi-Stage Flash Distillers, SWCC-O&M Symposium, Al-Jubail, Saudi Arabia, 1997.

[11] A. Malik, F.A. Aleem, Scale formation and fouling problems and their predicted reflection on the performance of desalination plants in Saudi Arabia, Desalination, 96 (1994) 409–441.
[12] O.A. Hamed, A.K.M. Al-Sofi, G.M. Mustafa, A.G.I. Dalvi, The performance of different antiscalants in multistage flash distillers, Desalination, 123 (1999) 185–194.
[13] O.A. Hamed, M. AK.Al-Sofi, M. Imam, K. BaMardouf, Evaluation of polyphosphonate antiscalant at a low dose rate in Al-Jubail Phase II MSF plant, Saudi Arabia, Desalination, 128 (2000) 275–280.
[14] O.A. Hamed, M. AK.Al-Sofi, K. BaMardouf, A. Al-Mobayed, A. Ehsan, Successful Operation of Multistage Flash Distillers at Low Antiscalant Dose Rate, Proc. 4th Annual Workshop on Water Conservation in the Kingdom, Center for Environment & Water, Research Institute, King Fahd University of Petroleum & Minerals, Dhahran, Saudi Arabia, 2001, pp. 23–25.
[15] O.A. Hamed, Lessons learnt from the operational performance of SWCC MSF desalination plants, Desal. Wat. Treat., 18 (2010) 321–236.
[16] O.A. Hamed, H.A. Al-Otaibi, Prospects of operation of MSF desalination plants at high TBT with low antiscalant dose rate, Desalination, 256 (2010) 181–189.
[17] O.A. Hamed, H. Al-Washmi, G.M. Mustafa, K. Bahardouf, F. Al-Shamri, R. Al-Bunain, E. Al-Rowely, Antiscalant tests at Al-Jubail plant could save SWCC $1/4 million/year, Int. Desal. Water Reuse Q., 14 (2004) 26–31.
[18] H. Böhmer, On-load Sponge Ball Cleaning System, Encyclopedia of Desalination and Water Resource, Chapter II, 1998.
[19] H. Böhmer, On-load tube cleaning systems and debris filters for avoidance of microfouling in MSF desalination systems, Desalination, 93 (1993) 171–179.
[20] M.A.K. Al-Sofi, Fouling phenomena in multistage flash (MSF) distillers, Desalination, 126 (1999) 61–76.
[21] O.A. Hamed, K. Bamardouf, A. Al-Omran, Impact of interruption of antiscalant dosing or cleaning balls circulation during MSF plant operation, Desalination, 208 (2007) 192–203.
[22] M.A.K. Al-Sofi, O.A. Hamed, K. Bamardouf, A. Dalvi, H. Al-Washmi, M.N. Kither, Y. Al-Aseeri, Availability safety margins of time and antiscalant dose rate, Desalination, 134 (2001) 241–247.
[23] A.M. Hassan, M.A.K. Al-Sofi, A.S. Al-Amoudi, A.T.M. Jamaluddin, A.G.I. Dalvi, N.M. Kither, G.M. Mustafa, I.R. Al-Tissan, A Nanofiltration (NF) Membrane Pretreatment of SWRO Feed and MSF Make-Up, Paper Presented at IDA Conference, Madrid, 1997.
[24] A.M. Hassan, M.A.K. Al-Sofi, A.S. Al-Amoudi, A.T.M. Jamaluddin, A.G.I. Dalvi, N.M. Kither, G.M. Mustafa, I.R. Al-Tissan, Part1, Desalination and Water Reuse, 8 (1998) 53–59.
[25] A.M. Hassan, M.A.K. Al-Sofi, A.S. Al-Amoudi, A.T.M. Jamaluddin, A.M. Farooque, A. Rowaili, A.G.I. Dalvi, N.M. Kither, G.M. Mustafa, I.R. Al-Tissan, A new approach to membrane and thermal seawater desalination process using nanofiltration membranes, Part 2, Desalination and Water Reuse, 8 (1998) 39–45.
[26] A.M. Hassan, A.M. Farooque, A.T.M. Jamaluddin, A.S. Al-Amoudi, M.A.K. Al-Sofi, A.F. Rubian, M.M. Gurashi, A.G.I. Dalvi, M.N.M. Kither, I. Al-Tissan, Optimization of NF Seawater Pretreatment, Paper Presented at 1999 IDA World Congress on Desalination and Water Reuse in San Diego, California, USA, 1999.
[27] M.A.K. Al-Sofi, A.M. Hassan, G.M. Mustafa, A.G.I. Dalvi, M.N.M. Kither, Nanofiltration as means of achieving higher TBT of ≥120°C, Desalination, 118 (1998) 35–51.
[28] A.M. Hassan, M.A.K. Al-Sofi, A.S. Al-Amoudi, A.T.M. Jamaluddin, A.M. Farooque, A. Rowaili, A.G.I. Dalvi, N.M. Kither, G.M. Mustafa, I.R. Al-Tissan, A New Approach to Membrane and Thermal Seawater Desalination Process Using Nanofiltration Membranes, Part 2, Water Science and Technology Association (WSTA) Proceedings, WSTA Conference, Bahrain, Vol. 2, 1999, pp. 577–594.
[29] A.M. Hassan, M.A.K. Al-Sofi, A.S. Al-Amoudi, A.T.M. Jamaluddin, N.M. Kither, G.M. Mustafa, I.R. Al-Tissan, A Nanofiltration (NF) Membrane Pretreatment of SWRO Feed and MSF Make-Up (Part-1), Report No. TR 3807/APP 96008, 1996.
[30] M.A.K. Al-Sofi, A.M. Hassan, O.A. Hamed, A.I. Dalvi, M.N.M. Kither, G.M. Mustafa, K. Bamardouf, Optimization of hybridized seawater desalination process, Desalination, 131 (2000) 147–156.
[31] M.A.K. Al-Sofi, A.M. Hassan, O.A. Hamed, G.M. Mustafa, A.I. Dalvi, M.N.M. Kither, Means and merits of higher temperature operation in dual purpose plants, Desalination, 135 (1999) 213–222.
[32] O.A. Hamed, A.M. Hassan, K. Al-Shail, K. Bamardouf, S. Al-Sulami, A. Hamza, M.A. Farooque, A. Al-Rubaian, Higher TBT, more product, less scaling, SWCC NF-MSF trial, Int. Desal. Water Reuse Q., 13 (2003) 23–27.
[33] O.A. Hamed, A.M. Hassan, K. Al-Shail, M.A. Farouque, Performance analysis of a trihybrid NF/RO/MSF desalination plant, Desal. Wat. Treat., 1 (2009) 215–222.
[34] A.A. Al-Hahiyrum A.S. Al-Amoudi, A.M. Farooque, Long term experience in the operation of nanofiltration pretreatment unit for seawater desalination at SWCC SWRO plant, Desal. Wat. Treat., 51 (2013) 1861–1873.