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Lessons learnt from the operational performance of SWCC MSF desalination plants

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ABSTRACT

Around 88% of water production by the Saline Water Conversion Corporation (SWCC) is provided by large MSF desalination plants which operate as power/water cogeneration plants. Despite the fact that the majority of SWCC MSF plants have been operating for more than two decades, their availability and water production as well as energy efficiency are still maintained within—or even sometimes higher—than the original design values. This is attributed to SWCC strict requirements of operation and maintenance which resulted in extending the life of the plants to more than thirty years.

In this paper, the energy efficiency of SWCC existing MSF desalination plants will be assessed. SWCC successful economic implementation of scale control techniques and the use of appropriate corrosion resistant materials will be highlighted. Benefits obtained from operating SWCC MSF desalination plants within the context of dual purpose plants employing either back pressure or extraction condensing turbine for the simultaneous production of water and electricity will be identified. Experience gained from the operational performance of SWCC MSF desalination plants will be effectively utilized to identify areas where savings in operating and capital cost could be realized in new MSF plants.

Keywords: SWCC; MSF; Operation; Performance; Experience

1. Historical background

The first two large long tube MSF plants which were built by SWCC in the early seventies, were Jeddah Phase-I (1970) and al-Khobar Phase-I (1974). Both plants were designed to operate at high top brine temperature of 121°C employing acid treatment. The distiller production capacity of each plant was 2.5 MGD. The major materials of construction, top brine temperature and general design philosophy of both plants were the same. A number of operational problems were experienced which resulted in very short life of both plants. Jeddah Phase-I was commissioned in 1970 and put out of service in 1980 after approximately ten years service. While Al-Khobar Phase-I was commissioned in 1974 and decommissioned in 1982 after approximately 8 years service.

Jeddah Phase-I apparently suffered from an undersized decarbonator [1]. This would have overloaded the deaerator with CO_2 reducing its air removal efficiency. Not only would the oxygen introduced to the recycle stream accelerate corrosion, but the CO_2 would lower the pH and lead to reduce acid addition (since the pH was monitored and controlled) and subsequently more CO_2 in the recycle stream. Such conditions did not provide satisfactory scale control. Although, operating at lower temperature (115°C) helped to extend the plant life, initial corrosion and scaling damage would have been difficult to correct. Lessons learned from the operation of Jeddah phase-I were reported [2]. Make-up water was being deaerated in the last stage of heat rejection. The brine recycle oxygen content was in the order of 100–150 ppb. External deaeration would have been employed to minimize the rate of corrosion. Rigid specification on the decarbonator must have been employed. For acid treated plant operating with 120°C top brine temperature, it is recommended that steam temperature to the brine heater must not exceed 5 to 6°C more than brine recycle exit temperature from brine heater.

Al-Khobar Phase I was a mirror image of Jeddah Phase 1 (OSW universal design) hence suffered from similar problems as experienced in Jeddah phase-I, but was also plagued with calcium sulphate scale. The initial specification required a design TDS of 45,000 mg/l. Soon after commissioning it was realized that sea water TDS was subject to diurnal changes from 45,000 mg/l to 59,000 mg/l. Such changes in the sea water TDS were not anticipated and forced the plant operation to drop the TBT from 120°C to 115°C [1, 3].

As a result, the threshold of hemihydrate calcium sulphate was frequently exceeded. The poor decarbonation (like Jeddah) which led to $CaCO_3$ scale provided situation for the deposition of $CaSO_4$, which adheres better to fouled tubes [1].

Jeddah Phase II went on stream in 1978 at 12.67 million gpd and 84 MW. Operational experiences gained and difficulties encountered in Jeddah Phase I were effectively utilized for the successful operation of Jeddah Phase II and extending its service life to approximately thirty years compared to ten years lifetime for Jeddah Phase I. An external deaerator was employed and the decarbonator performance was improved. Sodium sulphite was added to scavenge the residual dissolved oxygen. Operating top brine temperature was normally maintained at 115°C. It has been reported that bromine liberation caused extensive damage in noble materials of venting pipe. The presence of residual chlorine as low as 0.2 ppm and low pH, bromine would be liberated and would cause failure to 304 and 316L stainless steel [2]. Dechlorination by chemicals before acid injection was employed to prevent bromine attack. The plant was decommissioned in 2007.

Jeddah Phase III, commissioned in 1979 has four 62 MW extraction condensing steam turbine generators supplying pass out steam to a four 22,000 m^3/day MSF evaporator. The unique design of Jeddah Phase III compared to the previously built MSF distillers was the introduction of cross-tube arrangement. Cross-tube arrangement offers possible long-term maintenance advantages relative to the long-tube arrangement [4]. Experience gained from the operation of Jeddah Phase III was well documented [4]. Jeddah Phase III can operate both an acid and additive treatment mode. At present the plant is operating constantly with additive treatment and with good satisfactory operational performance.

In 1981, Jeddah Phase IV was commissioned. It incorporates 10 × 5.8 MGD MSF long tube evaporators. After more than twenty years of continuous operation, the plant experienced severe corrosion in the vapor side of the evaporator. Severe corrosion of the distiller components is attributed to the poor venting design of the evaporators. Recently, the plant was rehabilitated and the plant production increased by 20% more before rehabilitation and by 3% more from the original design [5]. The plant's average performance ratio increased from 6.42 to the design performance ratio 7 kg product/(2325.5 kJ heat input). The refurbishment work included modification of the venting and vacuum systems, change of the complete copper nickel tubes in each stage and lining of the area above demister including top roof, side roof and the side walls with 316L stainless steel lining. It is expected that the plant lifetime will be extended for more than fifteen years. The refurbishment investment was around 20% of the construction cost of a new plant.

2. Operational performance

A recent comprehensive study which was carried out by Saline Water Desalination Research Institute (SWDRI) of SWCC [6] revealed that MSF distillers which are over twenty years old, instead of being derated due to ageing, actually maintained production and performance ratios that equaled or, in most cases, surpassed the original design specifications. Thus, the service lives of these distillers are expected to exceed thirty years. This in turn, enhances the cost effectiveness of MSF process. The reasons for such good thermal performance were attributed to several design and operating conditions, such as:

1. Selection of conservative design fouling factors.
2. Effective alkaline scale control.
3. Selection of good construction materials.
4. SWCC strict operation and maintenance procedure.

It has been observed that high design fouling factors were selected for existing MSF plants. The design fouling factors (FF) of the brine heaters and heat recovery sections for additive plants range between 0.176 and 0.325 m^2K/kW, while the same for acid plants range from 0.0861 to 0.12 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 fouling factors results in the design of heat exchangers containing more surface area than required. Low values of design fouling factors such as 0.15 m^2K/kW, or even lower can be safely employed in new additive MSF designs.

However, selection of high design fouling factors for the existing MSF plants resulted in over-sizing of the heat transfer surfaces. This will allow these plants to operate at a top brine temperature equal to or even higher than maximum design values. The result is an increase in water production.

Operation experience acquired from the Al-Jubail desalination plant is unique. It is the biggest seawater desalination plant. It has forty six MSF distillers with a normal rated capacity of distillate production of 239 MIGD and a maximum installed capacity of 282 MIGD.

The Phase I plant consisting of six MSF distillers was commissioned in early 1981 while phase-II with forty distillers was commissioned in early 1983. The forty six distillers are still in continuous and satisfactory operation. Minor operational problems were encountered such as increase of first stage product water conductivity in one type of evaporators, clogging of suction screen of brine recycle and/or brine blow down pumps causing pump cavitation, rubber line damage in deaerators and have been successfully addressed [7].

Al-Jubail Phase-I plant comprises of 6 evaporators each a design capacity of 5 MIGD at TBT of 90.6°C. The most salient features of this plant are two-fold. First, all the evaporator tubes were made from titanium. Secondly, no external deaerator is employed. The plant performance since 1981 is very satisfactory. The plant was acid cleaned only once throughout its whole service life using hydrochloric acid in combination with nitric acid as inhibitor. The percentage of tube failure is negligible. Failures were neither corrosion or erosion related [8]. The major problem which was experienced by Al-Jubail phase-I was the deterioration of the plant's concrete structure especially in the seawater intake area. Structure repair work for seawater intake was completed successfully around one year back.

Al-Jubail Phase-II was overdesigned. The plant performance ratio during warranty period test was 15 to 30% higher than the corresponding design values. However, the plant is in most cases operated at TBT of 103°C for utilization of optimum turbine capacity and reduce thermal stress on plant components at the most economic cost [9]. Plant's overhaul schedule is prepared in such a way that out of the total 46 evaporators, at least 45 evaporators are in production during high water power demand period and at least 41 evaporators are operated during low demand period.

Al-Jubail Phase-II was firstly acid cleaned in 2002 after nineteen years of continuous satisfactory operation. As a result of acid cleaning, the plant performance ratio was improved and nearly approached the value obtained during the 1983 warranty period test [10].

A life assessment study was carried out for some of the major power and desalination components at Al-Jubail plant to extend its life for the next twenty years [11]. Among the tests which were conducted include eddy current and ultrasonic thickness measurements tests as well as visual inspections. Plants previous records were also reviewed. The study revealed that in general, Al-Jubail plant is in good condition with the adoption of some repairs, replacement, modifications and upgrade works. The plant will operate efficiently for the next twenty years without facing any serious problems. The rehabilitation cost will not exceed 10% of the original plant cost.

Yanbu plant phase-I, which was commissioned in 1982, operational experience is unique. The plant was originally designed to operate at a TBT of 121°C with acid treatment. The plant operating condition was then modified to operate in an alternating treatment mode. The plant operates with polymeric additive treatment at a TBT of 115°C with brine concentration ratio of 1.35 and dose rate of around 3 ppm. When the fouling factor reaches the design factors (a period of around 2 months), the plant seawater make-up treatment is switched to be operated with acid treatment for a one month period at TBT of 115°C to clean the tube and maintain a low fouling factor. The alternating treatment mode proved to keep the plant's water production and energy consumption at values comparable to the original design figures. The increase of the fouling factor during the additive treatment operation could be attributed to the low selected design fouling factor and the poor performance of the venting system, which were both originally selected to satisfy acid treatment.

3. Scale control

One of the main factors, which contributed to SWCC massive adoption of multistage flash distillation of seawater, is the application of successful methods for scale control. Formation of scale on heat transfer surfaces is a major operating problem in thermal desalination processes. It impedes the rate of heat conduction from the vapor that is condensing outside the tubes to the brine that is flowing inside the tubes, which will consequently reduce the distiller performance. Currently, as described in the previous section, the first generation of SWCC MSF plants have been employing acid treatment to control scale formation. But as a result of the complications associated with the control of acid treatment and the extensive corrosion of MSF main components, additive treatment was introduced. In the early seventies, polyphosphate compounds were initially adopted with its limitation on top brine temperature, brine concentration and contact time between brine and heat transfer surface. By late seventies high temperature additives were introduced in the market. The majority of MSF plants are currently using scale inhibitors such as phosphonates or polycarboxylic and polymaleic acids in conjunction with mechanical sponge ball cleaning to control alkaline scale formation. It is believed that chemical additives adsorb on the surfaces of sub-microscopic crystal nuclei and prevent them from growing or at least slow down the growth rate, hence scale formation. Antiscalants also disperse suspended solids which enhances scale crystal growth.

The SWCC being the largest producer of desalinated water in the world acquired vast design and operation experience that materialized in significant reduction of water production cost. A number of optimization tests had been carried out by SWCC and had led to successful operation at low antiscalant dose rates [12–19]. Recommended dose rates to SWCC in 1981 were 12.5 and 4.5 for TBT of 110 and 90°C, respectively and are currently reduced to only 2.0 and 0.8 ppm for the respective temperatures. This significant reduction in dose rate is attributed to several factors such as improvement in chemical formulation, adoption of on-line sponge ball cleaning and plants' operators awareness in reducing chemical dosing while maintaining effective plant performance.

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, which gets deposited on tube metallic surfaces, and induces resistance to heat transfer. The combined use of chemical additives and on-line tube cleaning has been proved to be the most cost effective means to combat scale formation and to avoid acid cleaning. Most of the MSF plants are employing on-load sponge ball cleaning. The ball to tube ratio for plants using chemical additive treatment varies from as low as 0.22 to as high as 0.45 with average frequency of three ball cleaning operations per day for all plants. The ball to tube ratio in MSF plants, thus in most cases, lie within the reported accepted range [20, 21]. Larger number of ball to tube ratio may cause problems by several balls passing one tube simultaneously and getting stuck while smaller ratio will not allow balls to reach all tubes. 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. Corrosion control

Corrosion control in SWCC MSF desalination plants is achieved through the proper control of the environmental conditions together with the proper selection of the materials of construction. The MSF units built in the seventies were employing modest deaeration of seawater feed make-up which was usually affected in the last flash stage. This usually caused heavy corrosion on the last stage and resulted in excess air in all stages inducing lower heat transfer and high corrosion rates. From the late seventies much attention has been given to deaeration of feed make-up by introducing separate efficient deaerators and also oxygen control by chemical additives.

The first generation of desalination plants which was installed in the Gulf region used carbon steel as the main construction material for the evaporator shells and internals [22]. Some significant changes had then occurred in the material selection specified for the second generation of desalination plants designed and constructed in the last decades due to deeper understanding of the operating conditions occurring inside the evaporator.

The most commonly used materials of construction in SWCC MSF plants are carbon steel, stainless steel, copper-nickel alloy and titanium [23, 24]. The shell of brine heaters of all plants is made of carbon steel and the tubes are either 70/30 or 90/10 Cu-Ni or modified 70/30 copper nickel (with 2% Fe and 2% Mn) except Al-Jubail Phase-I plant which is having titanium tubes. The material of construction of flash chambers is carbon steel with and without cladding. In some plants such as Al-Jubail, Al-Khafji II and Jeddah-III, the first high temperature stages are cladded with SS 316L. Module 1 of Jeddah II and the first two modules of Jeddah 1V are also cladded with stainless steel. Al Khobar II flash chambers are completely cladded with 90/10 Cu-Ni and Al Shqaiq flash chambers are also completely cladded with SS 316L or 317L. The material of construction of the heat rejection tubes of these plants are made of titanium except Jeddah plants which are having 90/10 Cu-Ni tubes.

Materials of construction of Shoaiba phase-II are to some extent unique [25]. The material of construction of the flash chamber is carbon steel lined with stainless steel (evaporator floor lined with 317L, side walls with 316L and top with 304L). Tube material for the first four stages of heat recovery are made of 66/30/2/2 copper nickel similar to brine heater. Tube material for the rest heat recovery stages is 90/10 copper nickel. Heat rejection tubes were made of 66/30/2/2 modified copper nickel.

The following measures are normally followed by SWCC to control corrosion in MSF distillers [25]:

1. Install sacrificial anodes in the water box of the heat rejection, heat recovery and brine heater

for controlling tube inlet, outlet and tube plate corrosion.

2. The liquid load of the external deaerator not to exceed 20 kg/sm^2 to get dissolved oxygen concentration in the deaerator effluent not exceeding 20 ppb.
3. To guarantee low dissolved oxygen in the brine recycle, addition sodium sulphite in the deaerator effluent is normally recommended.

The addition of sodium sulphite (Na_2SO_3) to deaerated seawater will be necessary when the performance of the deaerator will not yield a 20 ppb dissolved oxygen. It has been reported that addition of Na_2SO_3 to seawater containing up to 20 ppb dissolved oxygen has very little effect on the corrosion rates of evaporator and heat exchanger alloys [26].

5. Energy consumption

SWCC large MSF plants are operating within the context of dual-purpose plants for simultaneous production of power and water. Before the year 1983, most of the dual purpose power water plants were employing extraction condensing turbines. As the result of the improved thermal performance and efficiency of back pressure steam turbine [27] and the demand for water production, dual purpose plants which were built after 1983 were using back pressure steam turbines.

The energy consumption of a dual purpose plant is much lower compared to that consumed by a single purpose plant. A number of benefits would be obtained from the integration of desalting plants with power generation cycle. SWCC MSF distillers operating within the context of dual-purpose plants specific fuel energy consumption varies between 50 to 70 kWh/m^3 which is around 40 to 45% lower than that consumed by single purpose desalting plant. A recent comprehensive thermodynamic study [28] revealed that Al-Khobar Phase-III cogeneration cycle, which has a back pressure turbine arrangement and relatively high power to water ratio as compared to the Shoaiba phase-I, Shuqaiq and Al-Jubail Phase-II power/water cycle, has the highest fuel energy savings. The overall thermal efficiency of the plant could have been further improved if the steam withdrawn from the back pressure turbine would have been bled at pressure compatible with the thermal requirement of the brine heater and avoiding the throttling effect.

The SWCC introduced the concept of simple hybrid MSF/RO desalination concept to three of its large desalination plants: Jeddah, Al-Jubail and Yanbu plants. In 1989 Jeddah SWRO Phase-I desalination plant was built in the same site of Jeddah Phase 1 dual purpose MSF/Power plants. It consists of single stage plant and with a production capacity of 12.5 MIGD. In 1994, SWRO Phase II of 12.5 MIGD production capacity was combined with Phase-I [29]. The two SWRO phases are having common intake system. The products from the two single SWRO plants are blended with product water from an MSF/Power dual purpose plant of 80 MIGD product water.

As a result of the increasing water demand in the two cities of Madina and Yanbu, Yanbu Phase-I MSF/Power cogeneration plant was extended. A simple hybrid configuration incorporating four MSF distillers each with 8.7 MIGD production capacity and a SWRO plant of total production of 28.16 MIGD, was adopted [30]. A single stage RO process was selected. The MSF and RO desalination plants share the intake/outfall facilities and the products of the two processes are blended.

Al-Jubail MSF/Power dual purpose plants which are located on the Gulf coast of Saudi Arabia were extended by including a 20 MIGD single stage SWRO desalination plant in year 2000. The SWRO is sharing the intake/outfall facilities with the dual purpose MSF/Power Plant. The product of the SWRO and MSF desalination plants are blended.

As a result of integrating SWRO desalination plants with some of SWCC MSF plants, the specific fuel energy of water production was reduced from 60 to 58.4 kWh/m^2 in Al-Jubail plant, 55 to 47.4 kWh/m^3 in Jeddah plant and 53 to 40.7 kWh/m^3 in Yanbu plant.

6. Conclusions

1. SWCC MSF distillers which are over 25 years old, instead of being derated due to aging, actually maintained production and performance ratio that equaled or in most cases, surpassed the original design specifications. Thus, the service lies of these distillers are expected to exceed thirty years. This in turn, enhances the cost effectiveness of the MSF process.
2. Rehabilitation of MSF desalination built in the early 80's would result increasing the plant service life to more than forty years.
3. For acid additive plants: (a) brine heater fouling factor and steam approach temperature must be carefully selected at design stage, (b) materials of construction must be carefully selected, especially due to increased corrosivity in vent lines.
4. For additive treatment plants, antiscalant dose rates are reduced to as low as 2.0 and 0.8 ppm for top brine temperature of 110 and 90°C, respectively.
5. As a result of SWCC successful approach to control scale formation, design fouling factors less than 0.15 m^{2}K/kW can be safely employed in new additive MSF designs.

6. All SWCC MSF plants are employing on-line ball tube cleaning with a ball to tube ratio in the range of 0.22–0.45.
7. Corrosion control can effectively be achieved through the proper deaerator performance and the injection of sodium sulphite if the need arises.
8. Avoid the use of many redundant or standby equipment such as pumps and bypass of control valves.
9. Employ minimum thickness of noble metals for cladding and heat exchanger tubes.
10. Avoid the use of steam throttling valve upstream the brine heater and withdrawing steam from the turbine at the conditions just compatible with the heater requirements.
11. SWCC is the pioneer in introducing the concept of hybrid MSF/SWRO concept to its Jeddah, Yanbu and Al-Jubail desalination plants. The experience is a success and consequently resulted in lowering the water production cost.

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