EVOLUTIONARY DEVELOPMENTS OF THERMAL DESALINATION PLANTS IN THE ARAB GULF REGION[1]

Osman A. Hamed

Research &Development Center, SWCC,
P.O.Box 8328, Al-Jubail 31951, Kingdom of Saudi Arabia
Fax +966-3-343 1615, Email : rdc@swcc.gov.sa

ABSTRACT

The majority of large scale desalination plants in the Arab Gulf Region (AGR) employ thermal desalination processes. Around 2345 MIGD of desalinated water that accounts for 77% of the total water production in the AGR, was produced by thermal desalination processes in 2002. Due to its simplicity, reliability and huge capacity, the multistage flash (MSF) distillation process was the most dominant and frequently used process. It produced 94% of the total production of thermal desalination processes in the Gulf region. The multi-effect distillation (MED) coupled with thermal vapor compression (TVC) accounted for 6%.

The basic evolutionary developments which were introduced in the MSF process during the last four decades such as successful scale and corrosion control techniques and increase of distiller production capacity will be reviewed. The outstanding design and operating features of MED/TVC desalination plants that are responsible for their recent market emergence and competition to the MSF desalination plants will also be reported.

Thermal desalination plants are normally associated with power generation cycles. The evolutionary developments of the power/water cogeneration cycles will be discussed at length. Salient features of conventional power water cogeneration cycles in which the MSF distillation plant operates in association with either extraction or condensing or back pressure steam turbines, or in association with combined gas /vapor power generation cycles, will be reviewed. Characteristics of hybrid desalination processes

[1] Presented at Beirut Conference, 2004.

using a combination of MSF process with reverse osmosis (RO) process and power generation will be reported.

Current research efforts that are directed to enhance the evolutionary developments of thermal desalination processes will be presented.

1. INTRODUCTION

Desalination of seawater is expanding rapidly in the Arab Gulf Region. During the last fifteen years the total installed capacity of the desalination plants increased by two folds. According to an IDA report [1] and as shown in Fig.1, the total installed capacity of desalination plants in the Gulf Cooperation Council (GCC) states evolutionarily grew from 6.89 million m^3/day in 1988 to 13.8 million m^3/day in 2002 . Currently the total installed capacities of desalination plants in the GCC states is around 43 percent of the world's total installed capacity. Figure 1 shows that the majority of desalination plants in the GCC states are employing thermal desalination processes. In the year 2002, around 77% of the total installed capacity in the GCC is produced by thermal desalination processes. This could be attributed to the good experience in the region with such processes, the unfavorable seawater characteristics and the low cost of energy.

Breakdown of the capacity of the desalination plants in the GCC states in the year 2002 is shown in Fig.2. The Kingdom of Saudi Arabia is producing around 41% of the total production of GCC States. During recent years, the installed capacity of thermal desalination plants in United Arab Emirates grew significantly and is currently having nearly the same installed capacity of the thermal desalination plants in Saudi Arabia.

In this paper, the evolutionary developments which were associated with thermal desalination plants in the Arab Gulf region will be reviewed. Prospects of future developments will also be highlighted.

2. MULTISTAGE FLASH (MSF) DISTILLATION PLANTS

The multi-stage flash (MSF) distillation process in the Arab Gulf Region is superceding other conventional desalting processes. Although the MSF process was introduced more than forty years ago, the development of the process has been evolutionary rather than revolutionary. Development efforts were mainly directed towards the control of scale formation on heat transfer tubes by dose rate optimization of scale inhibiting chemicals and adoption of on-line sponge ball cleaning. Other areas of developments are selection of appropriate construction materials and increase of unit capacity.

2.1 Scale Control

One of the main factors, which contributed to the massive development 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. 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 Saline Water Conversion Corporation of Saudi Arabia (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 [2-9]. Recommended dose rates to SWCC in 1981 were 12.5 and 4.5 for TBT of 110 and 90 ^{o}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 [10&11]. 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.

2.2 Materials of Construction

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 [12]. 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 recent projects in the Emirate of Abu Dhabi use shells made of carbon steel cladded with stainless steel or solid stainless steel [12], carbon steel cladded with cupronickel for the water boxes, cupronickels for heat recovery tubes and titanium for heat rejection tubes.

The most commonly used materials of construction in SWCC MSF plants are carbon steel, stainless steel, copper-nickel alloy and titanium [13&14]. 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 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 stainless steel. 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 Shugayg flash chambers are also completely cladded with stainless steel. 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.

A comprehensive survey of the material of construction of MSF plants in the Middle East was recently reported [15]. The survey output was used as a basis to develop a guide for selecting standard construction material. However, the study did not reveal the operational problems and difficulties associated with the use of these materials. It has recently been argued that the use of solid duplex stainless steel for the flash chambers of MSF distillers will inherit a number of technical and economical merits [16].

2.3 Increase of Unit Capacity

The first MSF desalting plants were built in Kuwait in 1959 with a 1.0 MGD installed unit capacity. Since then the capacity of the installed unit in the GCC countries were continuously increased. Economy of scale has induced the design and construction of MSF desalination of large production capacities in order to reduce the specific installation and operational costs. The large size of these units implies high efficiency at steady state and relatively small flexibility during load variations. With fewer units of higher production capacity, the need for interconnection and control piping will be much reduced. The single unit is also simple to operate, and the number of operators required is smaller. SWCC distillers' water production capacities range from as low as 2.5 MIGD in the old plants up to 10 MIGD in the recently operated plants. MSF plants with maximum installed production capacities of 15 and 17.5 MIGD were recently built in Dubai and Abu Dhabi Emirates (UAE), respectively. The design characteristics of the two plants were reported [17].

2.4 Operational Experience

A recent comprehensive study which was carried out by SWCC [18] revealed that MSF distillers which are over 20 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 30 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.

3. MULTI-EFFECT DISTILLATION (MED) PLANTS

MED process is an old process and as the result of the scaling problems which are associated with the old design of these early units, the MSF process was introduced as an alternative in the 1960s. Recently considerable improvements in MED desalination systems have been introduced to reduce the undesirable characteristics of the old MED submerged tube evaporators such as low heat transfer rate and high scale rate formation. Falling film evaporators such as vertical tube evaporator (VTE) and the horizontal tube evaporator (HTE) of new MED plants have a number of distinct advantages [19]. They provide higher overall heat transfer coefficients and low specific heat transfer surface area when compared to multistage flash (MSF) desalination systems. They do not employ recycling and are thus based on the once through principle and have low requirements for pumping energy. Power consumption of MED/TVC plants is only around 2 kWh/m^3 as there are no requirements to recirculate large quantities of brine. The combination of high performance ratio and low power consumption results in lower overall energy costs. Multieffect distillation also offers the possibility of reducing plant size and footprint. However, there are some problems which are associated with MED systems such as the complexity of morphology and the limitation of production capacities.

MED process has recently made substantial progress for small thermal desalination plants. Historical evolution of the increase of the capacity of MED desalination plants in the GCC states is shown in Fig.3. MED production capacity increased during the period 1988 to 2002 exponentially from 0.037 million m^3/day to 0.66 million m^3/day [1].

In Saudi Arabia a number of small scale MED units working with either thermal or mechanical energy are located mainly along the East and West Coast of the Kingdom since 1979. SWCC built a reheat plant in the remote area of Al-Azziziya in 1987 with unit size of 1500 m^3/day . Operational experience of this plant revealed that the specified performance has been consistently satisfied and no major problems have so far been experienced.

The majority of MED plants in the GCC countries are situated in the United Arab Emirates (UAE). During the last four years, the installed capacity of the MED plant in UAE grew from 1.82 MIGD to 114.5 MIGD. In the 1982, six MED/TVC distillers were operated in different remote sites of Abu Dhabi (UAE) each had a rated production capacity of 1 MIGD [20]. The Taweelah desalination plants in UAE recently introduced 14 MED units as an extension to its existing MSF desalination plant [21&22]. The units were commissioned at the end of 2002. Each MED unit has a rated capacity of 3.77 MIGD. The applied MED technology is based on horizontal tubes with falling film evaporators and thermal vapor compression [22]. Each MED units consists of six effects. In order to prevent up-scaling difficulties and vapor flow rate limits, the first three effects are arranged in two identical rows of three cells. The top brine temperature is only 63^{o}C, in order to minimize scale forming on the tubes. Two MED units each with a rated capacity of 3.75 MIGD were installed in Umm Al-Nur. Operational experiences of these plants revealed that the specified performance has been obtained and no major problems have so far been encountered. The largest ever-used MED unit was commissioned in Layyah desalination plant in Sharjah (UAE) in 2001. It consists of two MED units each with a capacity of 5 MIGD. It has been reported that designs have been completed for individual MED units with capacities up to 10 MIGD [23].

4. POWER GENERATION CYCLES

Dual-purpose plants are widely used for simultaneous production of power and water. In dual purpose plants, the steam which is generated at high temperature and pressure, expands in steam turbines (thus producing work) before being supplied to the desalting plants. A number of possible arrangements of power/water co-generation systems can be achieved. In the case of water production by MSF distillation process, the distillers are normally coupled either with extraction condensing or back pressure steam turbine. Alternatively, power generation may be driven by gas turbines and thermal energy from their exhaust may be used to generate low (to medium) pressure steam in waste heat recovery steam generators (HRSGs). In such set-ups, steam may be routed directly or through back pressure turbine to the brine heater of distillation plants.

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 [24] and the demand for water production, dual purpose plants which were built after 1983 were using back pressure steam turbines.

The advantages of hybrid triple Power-MSF-SWRO over the dual Power-MSF and single purpose plants were reported [25-27]. The RO plant during cooler seasons (mainly in winter operation) will be fed with preheated water rejected from the MSF heat rejection section and this will result in the increase of the SWRO plant productivity and the reduction of energy required by the RO process. Such combination could also lower the cost of feed water intake systems and reduce chemical consumption due the high recovery ratio of the hybrid system. The blending of the products from MSF and SWRO allows for the use of a l-stage SWRO plant instead of the two stage SWRO plant normally employed in single purpose SWRO plants. All these factors should contribute to the lowering of the cost of desalinated water. Moreover, excess power production from the hybrid system will be reduced. This will consequently result in a low power to water ratio. A number of SWCC power-desalination projects are integrating MSF distillation and seawater reverse osmosis (SWRO) plants with power generation plants.

5. PROSPECTS FOR FUTURE EVOLUTIONARY DEVELOPMENTS

The majority of the existing MSF plants in the region are currently operating at top brine temperatures (TBT) between 90 and 110^{o}C .The top brine temperatures is limited by the solubility limits of calcium sulfate salts. The Research & Development Center (RDC) of the Saline Water conversion Corporation(SWCC) of Saudi Arabia recently introduced a promising approach for pretreatment of seawater using nanofilteration membrane(NF) [28-30]. Removing calcium, magnesium, bicarbonate and sulphate ions in the raw seawater by nanofilteration opened the possibility to safely increasing TBT of MSF distiller above 120^{o}C. A number of preliminary evaluation tests were recently carried out in an MSF pilot plant with a makeup feed produced from a nanofilteration process under different operating condition and without any antiscaling agents. It has been confirmed that the pilot plant can be operated safely and without any scaling problems up to a top brine temperature of 130^{o}C [31]. Increase of TBT to 130^{o}C resulted in 48% increase in water production. The technoeconmics of NF/MSF hybrid systems commercial application needs to be verified.

MED desalination plants are currently operating with top brine temperatures of around 65 ^{o}C to prevent scale formation. The use of nanofilteration pretreatment to MED plants would allow the high temperature operation of these plants without the danger of scaling. This is an area of technology that may well be worth exploring and this shall lead to successful replacement of MSF plants by MED technology [32].

Another research area which is worthwhile to be pursued is to explore the possibility of reducing the fuel energy consumption of power/water cogeneration cycles. Introducing innovative modifications to conventional power cycles such as the use of fuel cells instead of conventional fuel boilers will improve the exergetic efficiency of the power plant [33]. However fuel cell technology application is still in the pre-commercialization stage .

Combined gas-vapor cycles in which a gas power cycle (Brayton) topping a vapor power cycle (Rankine) are characterized by having higher thermal efficiencies than either of the cycles executed individually .Thermal performance of the combined cycle can further be improved if they are integrated with a variety of desalination processes as shown in Fig.4 [34]. Integration of gas and steam power generation cycles with thermal (MSF or MED) and membrane softening processes (NF and SWRO) will generate a number of operational benefits such as low power to water ratio, low energy consumption, high flexibility and consequently low production cost for both water and electricity.

6. CONCLUSIONS

1. Developments of cost-effective alkaline scale control approaches, good selection of construction material and strict maintenance procedures resulted in improved operational performance of MSF plants. The production capacities and performance ratios of MSF plants which operated for more than two decades are still maintained within or in most cases higher than the design values.
2. Taking advantage of economy of scale, unit installed production capacity of MSF distillers increased during the last four decades from 1 MIGD to 17 MIGD.
3. Increase of modular size of MED plants to 5MIGD resulted in its recent market emergence and competition with MSF desalination plants. Designs of individual MED units with capacities up to 10 MIGD are expected to be realized in the near future.

4. Recent trends of hybridization of thermal and membrane desalination processes improved the reliability, flexibility of operation and production cost of desalinated water.
5. Research efforts have to be focused to search for ways and means to facilitate high temperature operation of commercial MSF and MED desalination plants in order to improve efficiency and reduce water production cost.

7. ACKNLOWLEDGEMENT

The author appreciates the contributions made by Eng. Ali al-Wadie for data collection and Mr.Rafique Mubarak Imambaksh for typing and formatting.

8. REFERENCES

1. 2002 IDA worldwide desalting plants inventory, Report #17,prepared and published by Wangnick consulting GmbH.
2. Al-Mudaiheem, A.M.A and Szostack, R.M., (1986), Evaluation of Chemical Additives for Scale Control in MSF Plants, Topics in Desalination (13), SWCC, Saudi Arabia.
3. Nada, N., (1986), Evaluation of Various Additives at Al-Jubail Phase-I during Reliability Trials, Topic in Desalination No. 13, SWCC, Saudi Arabia.
4. Al-Zahrani, S., Al-Ajlan, A.M. and Al-Jardan, A.M., (1993), Using Different Type of Antiscalants at the Al-Jubail Power and Desalination Plant in Saudi Arabia. Proceedings of IDA and WRPC World Conference on Desalination and Water Treatment, Yokohama, Japan, Vol. 1, pp. 421-431.
5. M.AK.Al-Sofi, M.A.Al-Husain, A.A.Al-Omaran, and K.M.Farran, A Full Decade of Operating Experience on Al-Khobar-II Multistage Flash (MSF) Evaporators (1982-1992), Desalination, 96, (1994), pp. 313-323.
6. M.AK.Al-Sofi, S. Khalaf, and A.A.Al-Omaran, Practical Experience in Scale Control, Desalination, 73, (1989), pp. 313-325.
7. Hamed, O.A., Mohammad AK.Al-Sofi, G.M.Mustafa, and A.G.I.Dalvi, (1999), The performance of different antiscalants in multistage flash distillers, Desalination, 123, 185-194.
8. Hamed, O.A., et. al., (2000), Evaluation of polyphosphonate antiscalant at a low dose rate in Al-Jubail Ph-II MSF plant, Saudi Arabia, *Desalination*, **128**, 275-280.
9. Hamed, O.A.,, et. al., (2001), Successful operation of multistage flash distillers at low antiscalant dose rate, Proceedings of the 4th Annual Workshop on Water Conservation in the Kingdom, Center for Environment & Water, Research Institute, King Fahd University of Petroleum & Minerals, Dhahran, Saudi Arabia, 23-25.
10. Böhmer, H., (1998), On-load spong ball cleaning system. Encyclopedia of Desalination and Water Resource. Chapter II.

11. Böhmer, H., (1993), On-load tube cleaning systems and debris filters for avoidance of microfouling in MSF desalination systems, Desalination, 93, p.171.
12. Comado Sommariva, et.al., (2001), Forty-year design life: The next target material selection –conditions in thermal desalination plants, *Desalination*, **136**, 169-176.
13. Malik, A.U., and Mayan Kutty, P.C., (1992), Corrosion and material selection in desalination plants, Proceedings of the Seminar on Operation and Maintenance of Desalination Plants, SWCC, April 27-29, pp. 274-307.
14. Al-Mansour, A.H., et. al., (2001), Desalination industry development in the last two decades and its effect on production cost, Proc. Of IDA World Conference, Bahrain.
15. Oldfield, J.W., (2003), Survey of material usage in MSF plants over the past 25 years, Proc. of International Conference on Desalination, Bahamas.
16. Olsson, J., et.al., (2003), MSF chamber of solid duplex stainless steel, Proc. of IDA World Conference, Bahamas.
17. Borsani, R. and Ghiazza, E., (2001), MSF desalination units over 15 MIGD is becoming a reality and start a new age for the old technology, Proc. of IDA World Congress, Bahrain.
18. Hamed, O.A., (2000), Thermal performance of multistage flash distillation plants in Saudi Arabia, *Desalination*, **128**, 281-292.
19. Hamed, O.A., (1999), Thermal assessment of a multiple effect boiling (MEB) desalination system, *Desalination*, **86**, 325-339.
20. Michels, T., (1992), Recent achievements of low temperature multiple effect desalination in the western areas of Abu Dhabi, UAE, Proc. of Desal 92 Arabian Gulf Regional Water Desalination Symposium, Al-Ain, UAE.
21. Sommariva, C. and Syambabu, V.S.N., (2001), Increase in water production in UAE, *Desalination*, **138**, 173-179.
22. Vermey, J. W.. and Berand, D., (2001), Breakthrough of MED technology in very large scale applications, Taweelah Al-Case, Proc. of IDA Conference, Bahrain.
23. Banjat, V. and Bukato, T., (2003), Research & Development towards the increase of MED unit capacity, Proc. of IDA Conference, Bahamas.
24. Hamed, O.A., et.al., (2001), Power/Water cogeneration cycles, Proc. of IDA World Congress on Desalination and Water Reuse, Manama, Bahrain, October.
25. Sommariva, C., et.al., (2001), Matching power and desalination by combining thermal and membrane processes: The alternative to improve flexibility and performance, Proc. of IDA World Congress on Desalination and Water Reuse, Manama, Bahrain, October.
26. Park, J.K., et.al., (2003), Application of hybrid technology to the largest desalination plant, Fujairah, UAE, Proc. of IDA World Congress on Desalination, Bahamas.
27. Misra, B.M., et. Al., (1999), Futuristic trends in hybrid system for desalination, Proc. of IDA World Congress on Desalination and Water Reuse., San Diego, USA.
28. Hassan, A.M., Farooque A., Jamaluddin, A.T.M., Al-Amodi, A.S., Al-Sofi M.AK., Rubian A.F., Gurashi, M.M., Dalvi, A.G.I., Kither, M.N.M. and Al-Tissan, I. (1999), Optimization of NF Seawater Pretreatment, Paper presented at 1999 IDA World Congress on Desalination and Water Reuse in San Diego, California, USA, 29/8 to 3/9. (Paper received best paper award), 1999.

29. Al-Sofi M.AK, Hassan, A.M., Hamed O.A., Dalvi, A.I., Kither, M.N.M., Mustafa, G.M., and Bamardouf, K, (2000), Optimization of Hybridized Seawater Desalination Process, J. *Desalination*, Vol. **131**, 147-156.
30. Al-Sofi M.AK., Hassan, A.M., Hamed O.A., Mustafa, G.M., Dalvi, A.I. and Kither, M.N.M., (1999), Means and Merits of Higher Temperature Operation in Dual Purpose Plants, *J. Desalination*, Vol. **135**, 213-222.
31. Hamed, O.A., et.al., (2003), Operational performance of an integrated NF/MSF desalination pilot plant, Proc. of IDA World Congress on Desalination and Water Reuse, Paradise Island, Sept.-28 – October 03, Bahamas.
32. Hanbury, B., (2001), The future of seawater desalination – some thoughts, Workshop on Water Conservation in the Kingdom, Center for Environment and Water, Research Institute, KFUPM, Dhahran, Saudi Arabia, April 23-25.
33. Dunbar, W.R. and Lior, N., (1991), Combining fuel cells with fuel fired power plantsa for improved exergy efficiency, J. Energy, Vol. **16**, No. 10. 1259-1274.
34. Hamed, O.A., et,al., (2001), Prospects of improving energy consumption of the multi-stage flash distillation process, Workshop on Water Conservation in the Kingdom, Center for Environment and Water, Research Institute, KFUPM, Dhahran, Saudi Arabia, April 23-25.

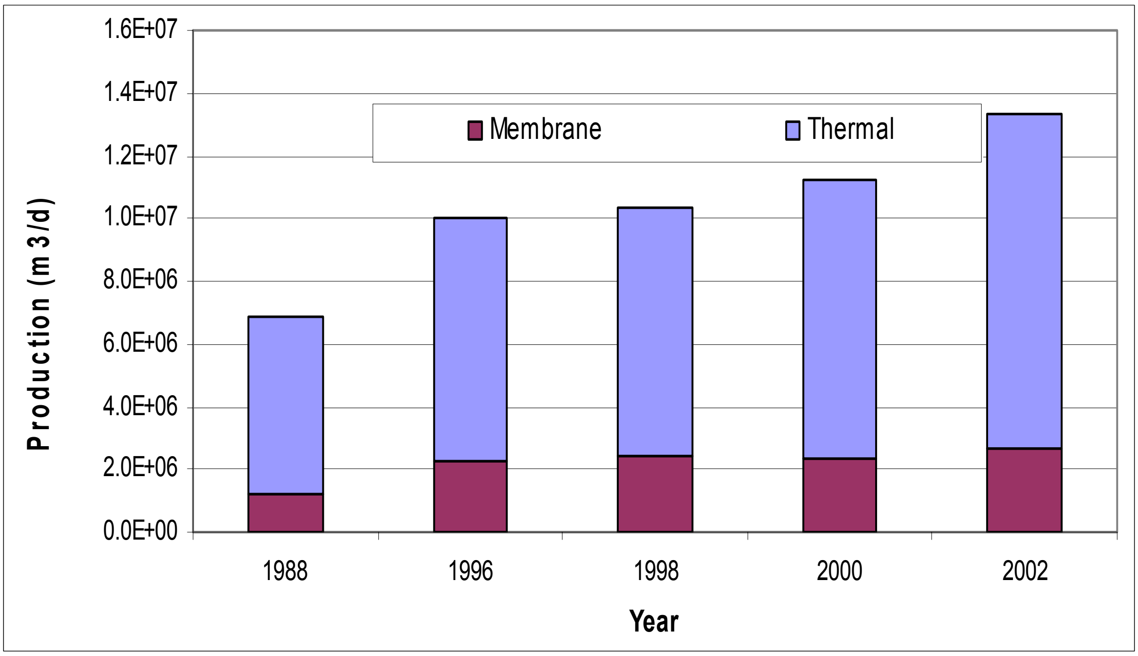

Figure 1. Historical evolution of the total installed capacities of desalination plants in GCC countries

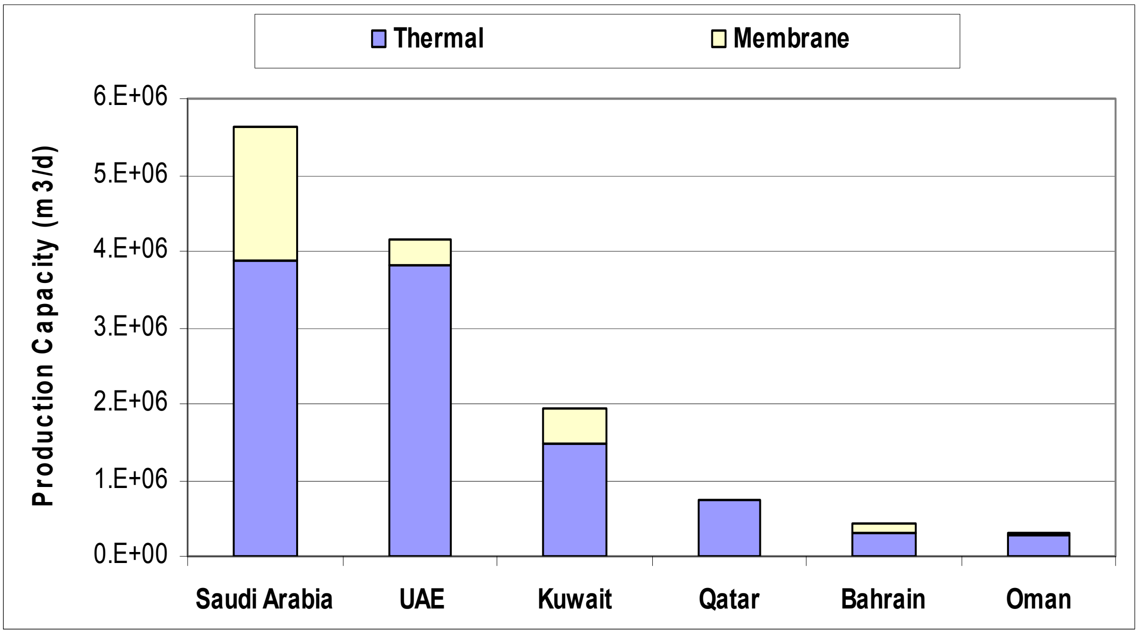

Figure 2. Breakdown of the capacity of GCC desalination plants in the year 2002

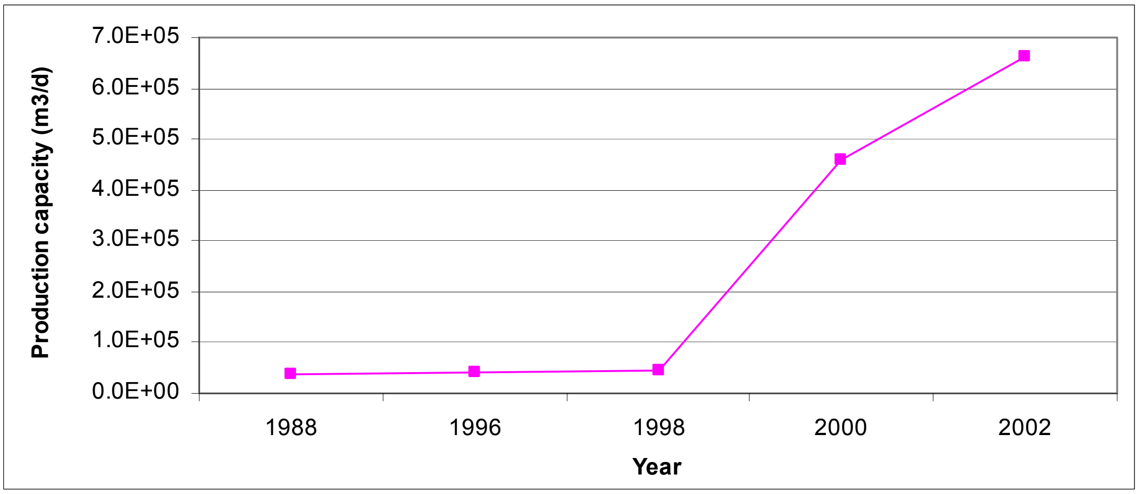

Figure 3. Historical evolution of the installed capacities of MED desalination plants in the GCC states

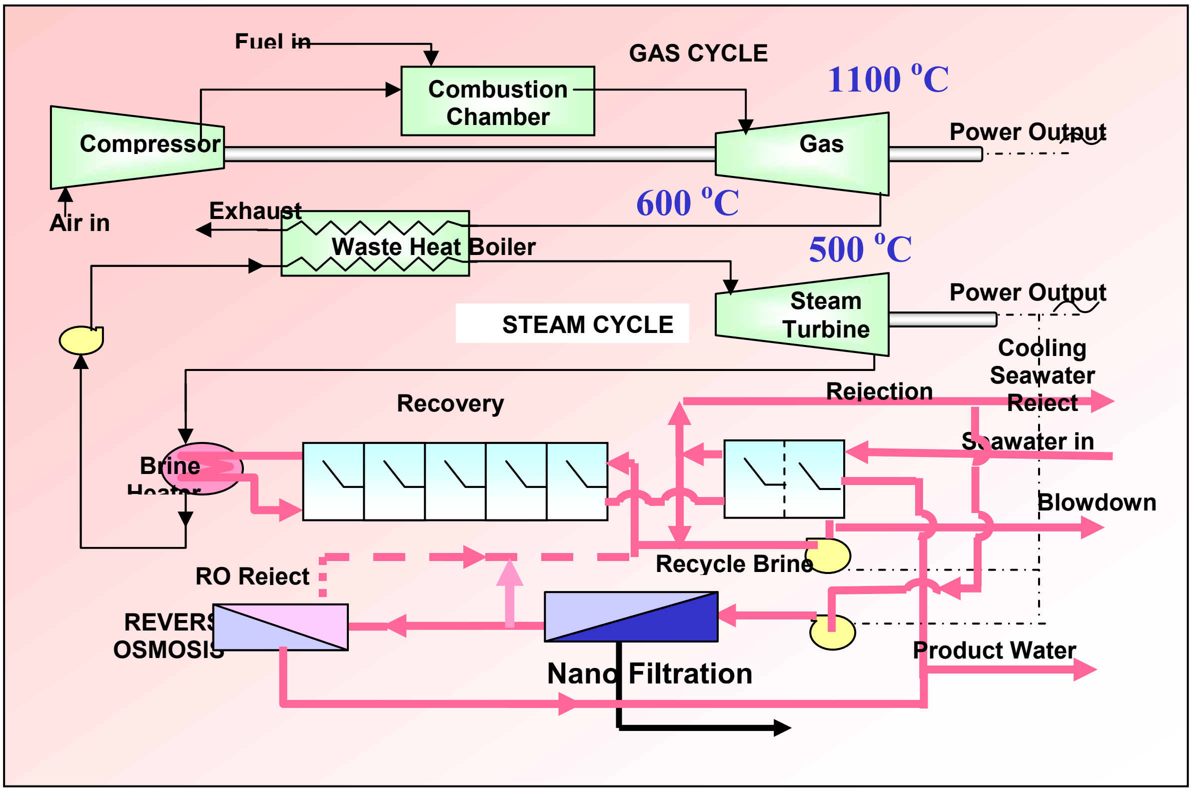

Figure 4. Combined power generation cycle integrated with NF/MSF/RO desalination plants