Desalination and Water Treatment
www.deswater.com
doi: 10.5004/dwt.2022.28076

259 (2022) 244–251
May

Pilot plant evaluation of 95°C TBT MED-TVC desalination technology

Amr Mohamed Mahmoud*, Khalid Bamardouf, Ahmad Al Ghamdi, Sultan Ahmed

Thermal Department, Desalination Technologies Research Institute, Saline Water Conversion Corporation (DTRI-SWCC), Jubail, Saudi Arabia, emails: amahmoud4@swcc.gov.sa (A.M. Mahmoud), kbamardouf@swcc.gov.sa (K. Bamardouf), aal-ghamdi34accb@swcc.gov.sa (A. Al Ghamdi), sultanahmed.phd@gmail.com (S. Ahmed)

Received 26 May 2021; Accepted 24 November 2021

A B S T R A C T

Multi effect distillation (MED) has recently led the thermal desalination market after leaving the MSF process behind amongst the thermal processes. Integration of vapor compression with MED (TVC-MED) led to an enhancement in the economics of MED compared to MSF. On the other hand, as thermal desalination still has leverage in terms of operational experience and reliability, the Desalination Technologies Research Institute (DTRI) initiated a long-term research project for 5 y aimed at MED performance enhancement. In this paper, the successful attempt at increasing the top brine temperature (TBT) of the MED process from conventional 65°C to 95°C with anti-scalant has been discussed. This approach has technical and economic advantages over acid treatment. Such an increase in TBT will increase the operating temperature range of MED by a factor of more than two, which will be reflected directly in system efficiency and improved MED-TVC economics.

Keywords: Multi effect distillation; Scale; Desalination; Techno economic

1. Introduction

Desalination offers the potential of an unlimited source of fresh water purified from the vast salt water that surrounds us. Currently, about 57% of the present desalination capacity of 97.2 million m^3/d is produced from seawater [1]. In the future, much of the expected growth will come from seawater due to continued development of the market in coastal-based water poor regions surrounding the Arabian Gulf, the Mediterranean Sea, and the Red Sea [2]. The global water desalination market is estimated to be valued over USD 32 billion by 2025. This can be attributed to the increasing population, less availability of freshwater bodies, increase in industries resulting in an increase in water requirement [2]. The main dominant technologies in the market are reverse osmosis (RO), multi stage flash (MSF) and multi-effect distillation (MED). MED has a share of 6.9% in the total global installed seawater desalination capacity [3]. MED is the preferred technology for brine evaporation and brine concentration and is able to handle higher levels of chemical oxygen demand (COD) and total suspended solids (TSS) with very minimal pre-treatment. The 300,000 m^3/d Zhoushan Island MED plant is likely the largest MED plant, and was built along with membrane desalination plant to serve a refinery in China [4].

Thermal desalination technologies have relatively high reliability under severe seawater conditions. There is also a significant potential to reduce energy consumption of thermal desalination technologies [5,6]. Al-Mutaz describes the salient features of MED-TVC systems which makes it one of the most promising desalination technologies [7]. A MED-TVC system consumes a lower amount of electrical energy compared to the MSF technology and a conventional MED [8–11]. During the 1990s and early 2000s, MED-TVC systems were limited in unit capacities

* Corresponding author.

Presented at the European Desalination Society Conference on Desalination for the Environment, June 20–23, 2022, Las Palmas de Gran Canaria, Spain
1944-3994/1944-3986

[12], but the 15 MIGD unit of the Yanbu Phase 2 plant and the 20 MIGD unit of Al-Shoiaba plant in Saudi Arabia are examples of a modular evaporator concept which allows to build evaporators with any unit capacity considered as practical and economical [8].

A possible high performance ratio (PR) of the MED-TVC can result in considerable reduction of steam consumption for the same water production in a cogeneration configuration [12] and would be the preferred form of thermal desalination technology in concentrated solar power (CSP) assisted cogeneration [13]. A higher top brine temperature (TBT) increases the operational temperature range of a MED-TVC system, allowing the design of MED evaporators with a larger number of effects, which results in an increased PR [8].

While in an MSF process a forced brine flow inside the heat exchanger tubes leads to relatively uniform concentrations of the brine exposed to the heat exchange surface area, the concentration of a falling film applied to the outside of the tube bundles in a MED-TVC system can vary in a wide range due to factors like uneven feed water distribution, uneven evaporation, blocked nozzles, etc. Also, the MSF process includes a ball cleaning system to remove soft scales which are generated inside the tubes during operation, but scale formed in MED-TVC would be difficult to remove. For those reasons, MSF plants have been generally designed to be operated at higher TBT of 112°C, while existing conventional MED-TVC plants have been designed with a TBT in the range of 65°C to prevent scale occurrence. An advanced MED-TVC technology with a TBT of 85°C has been successfully developed through analytic and experimental studies in Korea [14–18]. This was verified in Saudi Arabia by running a 24 ton/d pilot plant at DTRI-SWCC.

Previously, an increase in the TBT of the MED system was attempted by softening the water using NF before the MED. Using this approach, the TBT was successfully increased from 65°C to 95°C and then to 125°C [19]. As NF requires a rigorous pre-treatment process similar to RO and additional cost of operation and capital cost. In addition adding compete system would lead to reduce overall system reliability [20].

To further increase the TBT without any aid of softening, which has less impact in cost. The MED-TVC pilot plant was operated over a period of four months at a TBT of 95°C using hybrid acid/antiscalant pretreatment [22] and then using antiscalant alone. The impetus for this evaluation test were the promising results obtained during the TBT 85°C test conducted in cooperation with Doosan [17] and the previous experience of DTRI-SWCC in operating MED with acidified feed to inhibit the scale formation at Aziziah plant in Jeddah [21]. Adoption of both the techniques enabled the unit to operate at a higher TBT of 95°C. The pilot plant showed stable performance during the entire operation period.

The objectives of the pilot test were:

- To validate the stable operation at a TBT of 95°C with antiscalant.
- Avoid the corrosion potential which may result from acid treatment which was applied in hybrid acid/antiscalant pre-treatment [22]

2. Experimental methodology

2.1. Pilot plant equipment description

The parallel feed MED-TVC pilot plant shown in Fig. 1 is located at the Desalination Technologies Research Institute (DTRI), Saline Water Conversion Corporation (SWCC) in Jubail in the Kingdom of Saudi Arabia (KSA) on the Arabian Gulf coast. The distillate production capacity of the pilot plant is 24 m^3/d with a makeup seawater flow rate of 3.2 m^3/h. The flow diagram of MED process is shown in Fig. 2. In the MED, the seawater is heated up by rejected brine and distillate passing through plate heat exchangers. Then, it enters the MED effect (i.e., top side of evaporator) to condense the vapor inside the tubes and gain heat. The heated seawater evaporates at corresponding temperatures in each effect, and brine is sequentially moved from effect to effect. The distillate is produced by brine heating in each effect. The TVC gets the suction steam from the fourth effect. There are also two additional TVCs for sucking the steam from the second and third effects. However, only the TVC sucking from the fourth effect was used, as optimization of the TVC location was not a priority during this project.

Although the pilot plant has small bundle compared to 2.5 MIGD module used in commercial units such as

Fig. 1. High Temperature – MED (HT-MED) pilot plant in DTRI, Jubail, KSA.

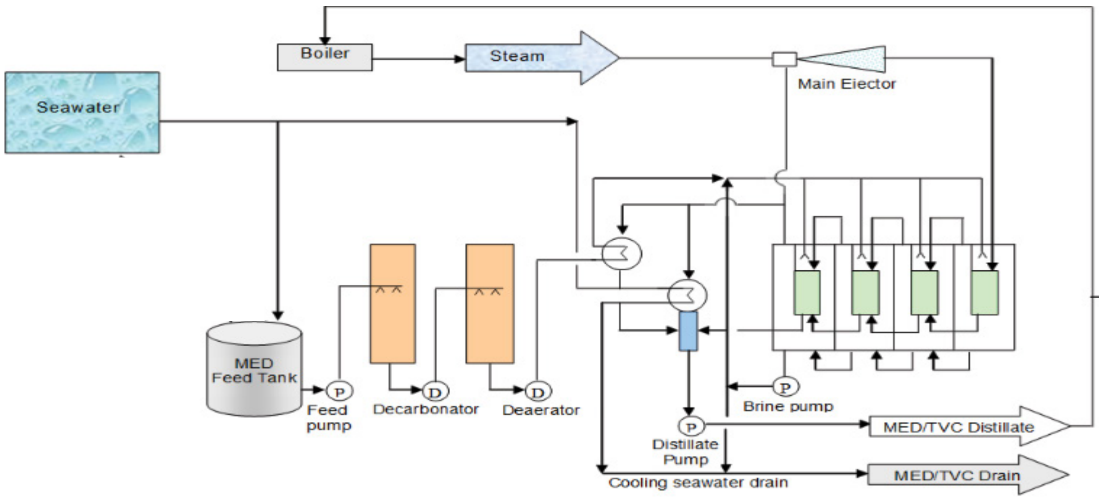

Fig. 2. The flow diagram of MED-TVC process.

Yanbu plant, the process design considering the worst part of the bundle by this design which ensure minimum liquid loading and maximum salinity within commercial system. By this approach the pilot mimic the lower part of the commercial size bundle.

2.1.1. Boiler

The MED-TVC unit receives steam from a steam header coming from the boiler room. The boiler has a capacity of 2,000 kg/h and is of the fire tube (FT) – RF type. Its working pressure is 12 bar and the hydro test pressure is 21 bar.

2.1.2. Evaporator

The MED plant has 4 effects with tray type feed system (tray + perforated plate) and contains two passes. The tubes in the evaporator are made of titanium and are 3.6 m in length, 18.88 mm in diameter and 0.7 mm in thickness. The distance between the tubes is 9.5 mm and they are arranged in a triangular pattern. First pass has 100 tubes and the second-pass has 13 tubes, with 16 rows and 2 rows, respectively

Some of the main differences between the HT MED pilot test setup and the commercial MED plants are listed in Table 1.

The lower parts of the tube bundle in a MED plant are subject to the harshest conditions in terms of salinity increase, due to evaporation over the upper rows of tubes. Brine recirculation configuration was adopted to ensure that the pilot plant would be subject to the same concentration factor as seen in commercial MED plants of large capacity. An additional harsh condition was imposed by having a lower liquid loading rate of 0.036 kg/m s (Table 2), which is lower than the liquid loading rate applied on the tubes in commercial MED plants.

2.2. Scale treatment

A commercial polymeric phosphate based antiscalant was dosed at 6 ppm in the makeup seawater to control alkaline scale formation expected to be generated from the residual bicarbonate ions. The recirculation of the brine likely aids in scale prevention at higher TBTs, as long as the residence time of the brine is less than the time for which the antiscalant is active. This strategy was commonly adopted in MSF plants [24].

Since the first effect experiences the highest temperature, the success of the trial test should be assessed based on the following criteria:

- stability of the first effect's heat transfer coefficient;
- the fouling factor in the first effect and;
- visual inspection of the first effect.

Table 1
Summarize the pilot plant information

Boiler type	Fire tube boiler
Fuel	Diesel
Motive steam pressure	xx bar
Steam temperature	
Flow rate of steam	
Entrainment ratio	
Top brine temperature	
Brine temperature	
Maximum salinity	
Concentration ratio	

2.3. Performance evaluation

2.3.1. Thermal performance results

Detailed thermal calculations were carried out during the entire test period to closely monitor the performance of MED to confirm the good performance and safe operation conditions. The slope of heat transfer coefficient, fouling factor and MTD showed a stable trend with minimal slope.

Temperatures and flow profiles TBT, feed, make up sea water, steam and vapor in each effect exhibited stable

Table 2
Comparison between the MED pilot test setup and a commercial conventional MED plant ([23])

Description	MED pilot unit	Yanbu MED
TBT (°C)	95	65
Feed heating preheaters	No	Yes
Feed type	Parallel	Parallel
Feed method	Tray type	Nozzle type
Liquid loading rate (kg/m/s)	0.036	0.05
Max BBD TDS (ppm)	65,000	60,600
Number of effect	4	5
GOR	3–4	7
Brine recirculation	Yes	No

temperatures profiles during the testing period as shown in Figs. 4 and 5.

Based on the obtained data, using MTD (mean temperature difference = Vapor temperature inside the effect-vapor temperature inside effect condenser tube) and the overall heat transfer coefficient (HTC) for each effect, fouling factors (FF) were calculated. The procedure for calculating the HTC (U) and FF [17]. Fig. 6 shows the MTD, the HTC and the FF. The FF was below the design FF. The HTC (U) and FF were calculated as follows: $U = Q/(A \cdot \Delta T)$, gained output ratio (GOR) is a measure of how much thermal energy is consumed in a desalination process, typically defined as the number of kg of distilled water produced per kg of steam consumed (1).

$$\mathrm{FF} = \frac{1}{U_f} - \frac{1}{U_c} \tag{1}$$

From Fig. 6 it is clear that overall heat transfer coefficient and MTD is directly linked, increase in fouling lead to reduce in overall heat transfer coefficient and to keep same amount of heat transfer increase of MTD is required ($Q = U \cdot \mathrm{Area} \cdot \mathrm{MTD}$). As discussed earlier, TBT increase would allow increasing the number of effects and hence increasing the system efficiency. However, MED-TVC system is complicated and a detailed study must be considered to have clear picture. As a role of thumb, the advantage gained by increasing the TBT could be shown as an increase in system efficiency and reduction in OPEX (due to higher Gain Output Ratio GOR) or reduction in capital cost (reduction in heat transfer area).

In the case of fixing the GOR and allowing the steam heat transfer area to change, increasing in the TBT up to 95°C would reduce the heat transfer area more than 55% as shown in Fig. 7.

2.3.2. Visual inspection results

At the end of the 4 month testing period with 6 ppm dosing rate, an inspection was performed in order to confirm the thermal performance results. Figs. 8 and 9 show the tube surfaces of a whole effect before and after the 4 months testing period. After the test, no scale was found on the tube surfaces. Only thin layer of scale was observed on tubes which has dry zone, that is, the layer related to water distribution no anti scale performance.

3. Cost analysis

A comparison between different technologies of desalination had been published in GWI comparing the cost of different technologies shown in Fig. 10. The main target is to reduce the steam cost and make more economic.

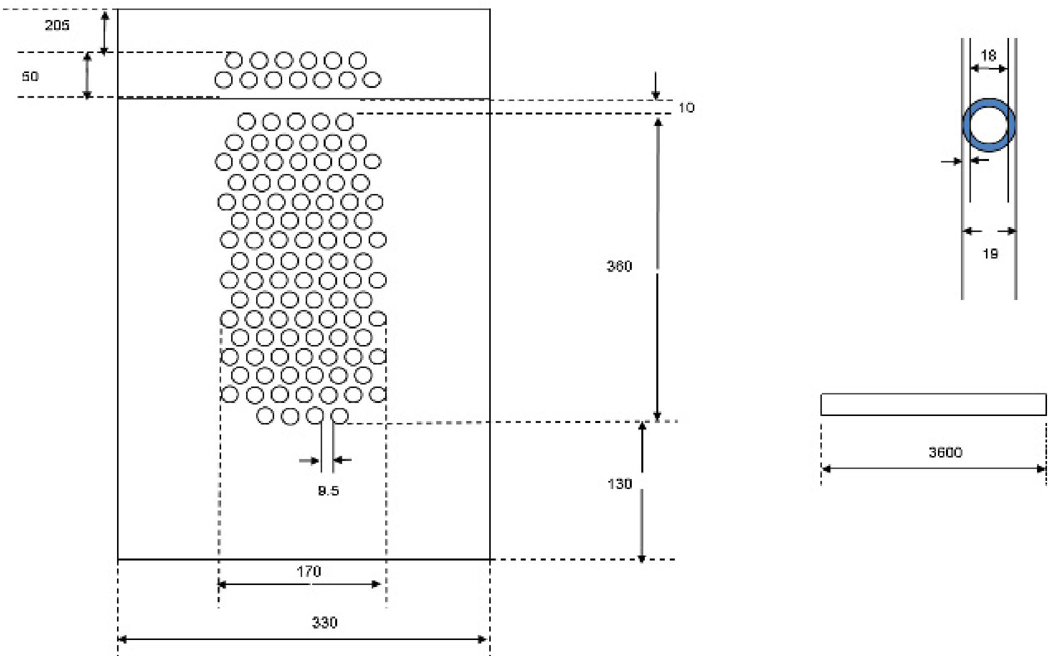

Fig. 3. Two pass arrangement of the tube bundles. Also shown are the diameter, the thickness and the length of the tubes.

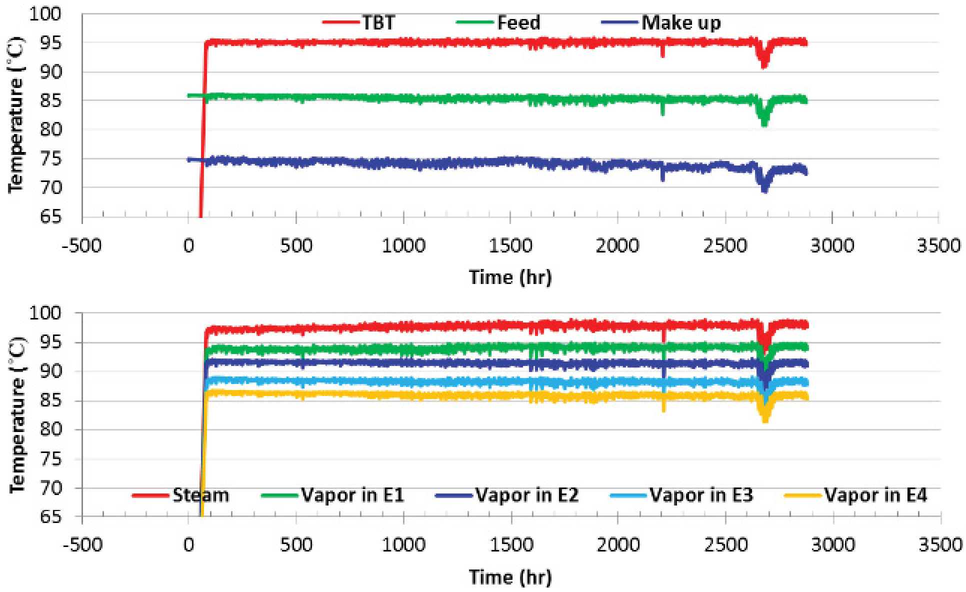

Fig. 4. Temperature profiles of top brine temperature, feed, make-up seawater temperature, steam and vapor temperature in individual effect.

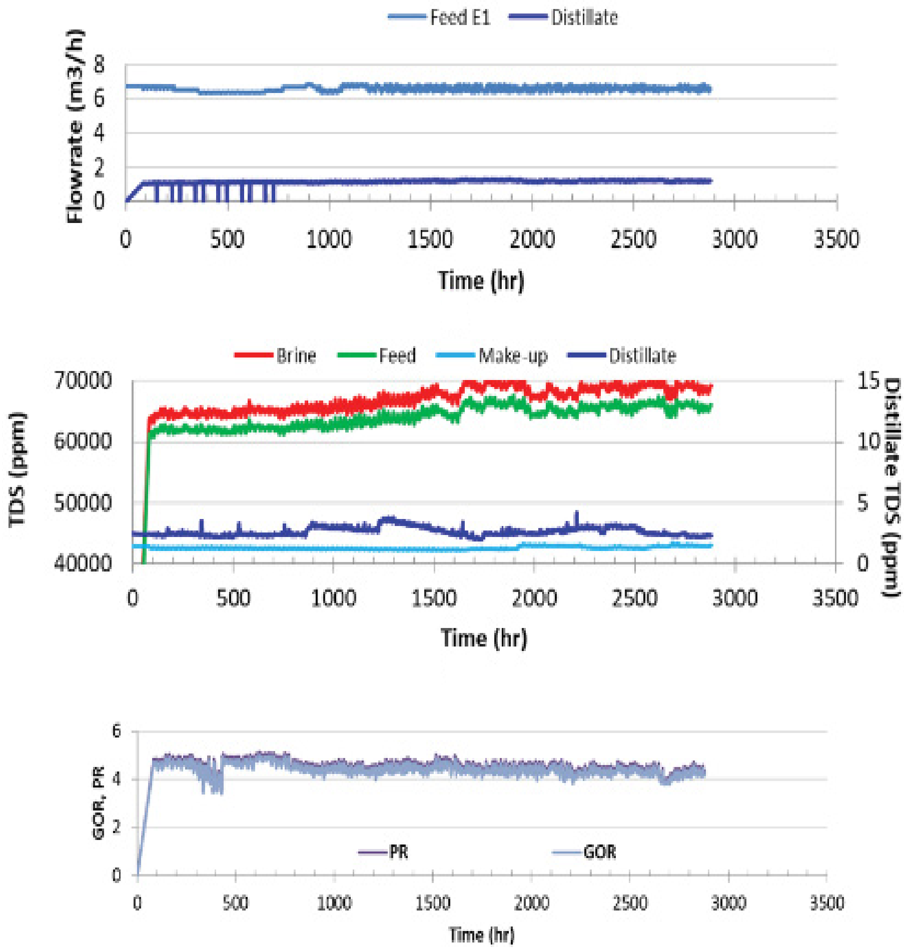

Fig. 5. Profiles of flow rates, concentrations, PR and GOR. Distillate TDS is shown on the secondary *y*-axis.

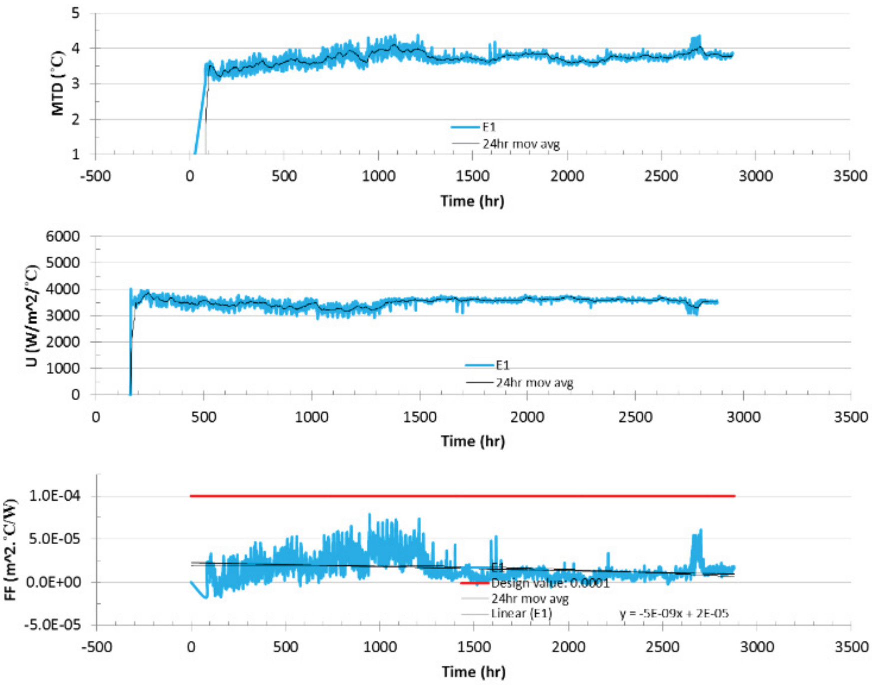

Fig. 6. MTD, overall HTC and FF.

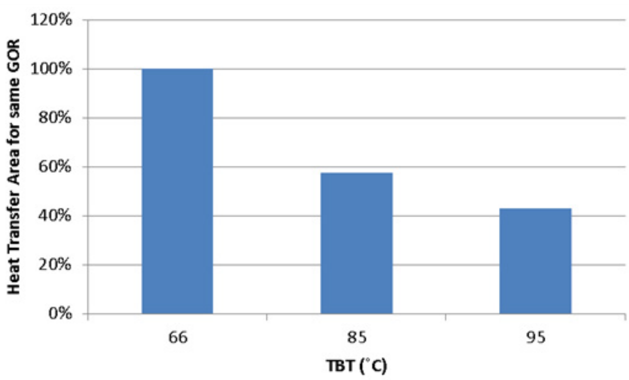

Fig. 7. Decrease in heat transfer area with increase of TBT with the same GOR.

Based on data extracted from Ras Al Khir plant and Jeddah RO phase 3. An economic analysis was performed to compare the levelized cost of water (LCOW) of a MED-TVC operating at a TBT of 95°C with a standard MED TVC working at 65°C and 85°C and MSF thermal process. The LCOW including both CAPEX (i.e., material, civil, erection cost, and transportation cost) and OPEX (i.e., steam, power, chemical, O&M cost) for each plant have been calculated based on a capacity of 2.5 million imperial gallon per day (MIGD). Furthermore, the water cost has been based on an oil price of 50 USD/barrel, 30 y plant life time, a discount rate of 5%, and electricity cost of 0.026 USD/kWh. The thermo-physical properties (i.e., mass, temperature, salinity, and enthalpy) of all process streams (i.e., steam and seawater) were determined as a function of temperature, pressure, and salinity based on heat and

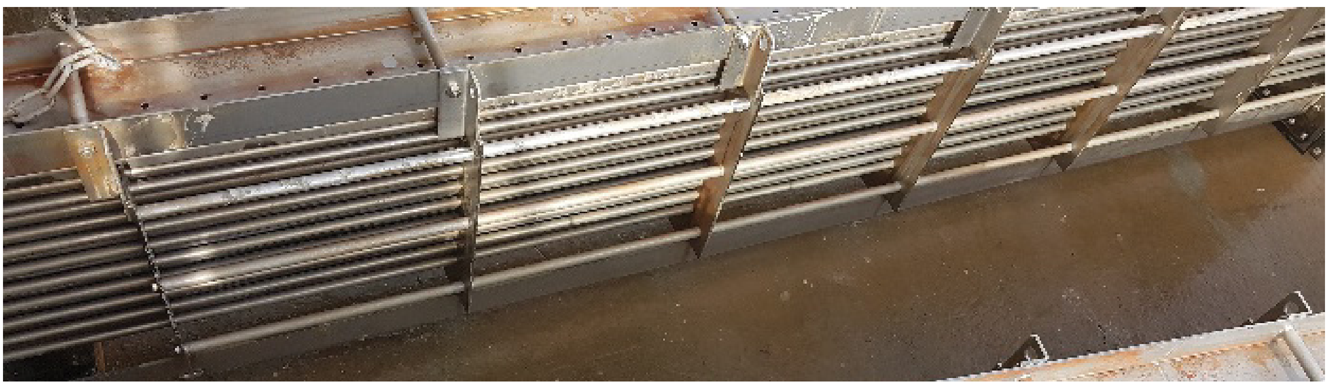

Fig. 8. Visual inspection before test.

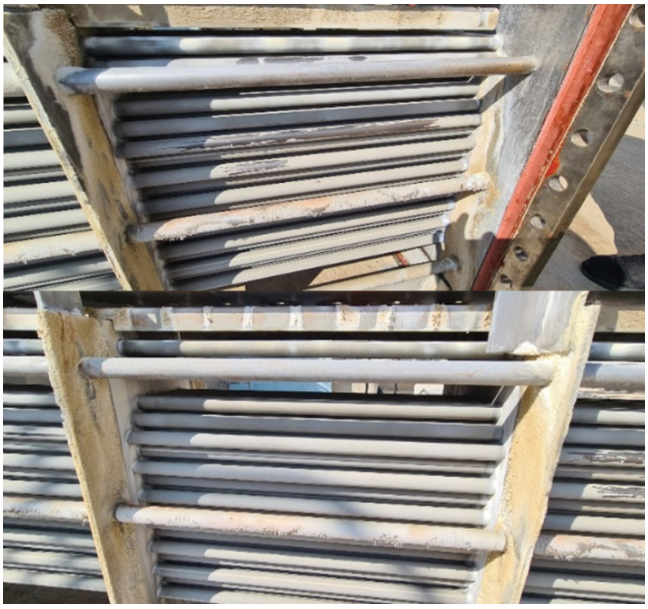

Fig. 9. Overall view for effect 1 bundle after test.

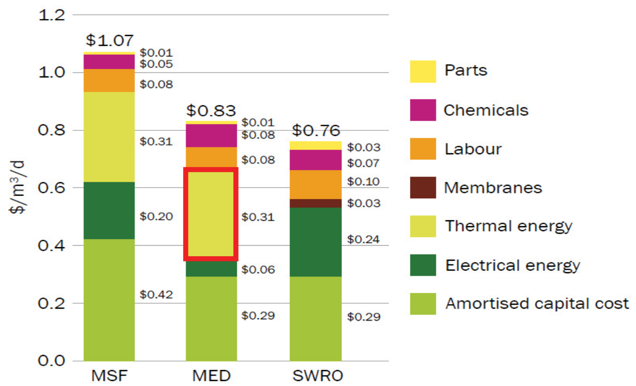

Fig. 10. Relative operating costs of the main desalination process. [25]

mass balance equation of each process at the given fixed conditions (i.e., feed condition, capacity, TBT, and so on). As a result, based on the techno-economic program owned by DTRI a comparison of MED TVC cost shown in Fig. 11, the TBT 95°C MED-TVC plant shows 16% lower LCOW compared to MED TVC at TBT 65°C. Therefore, it can be suggested that TBT 95°C MED-TVC is a financially competitive and technologically reliable option in the Gulf area which has challenging seawater characteristics.

4. Conclusion

In this study, the advanced high TBT 95°C MED-TVC was discussed based on experimental and techno economic study results. The following conclusions can be made: extensive and rigorous tests which were conducted in a MED pilot plant confirmed that it is possible to operate the plant at a top brine temperature (TBT) of 95°C safely without scale formation. Currently, all operating commercial MED-TVC plants are operating at a TBT of 65°C. Techno-economic study revealed that operating the MED TVC at TBT 95°C rather than 65°C shall reduce steam consumption by more than 34%, and consequently the levelized cost of water shall be reduced by 16%. One of the other advantages would be a reduction in the size of the TVC.

References

[1] J. Eke, A. Yusuf, A. Giwa, A. Sodiq, The global status of desalination: an assessment of current desalination technologies, plants and capacity, Desalination, 495 (2020) 114633, doi: 10.1016/j.desal.2020.114633.

[2] Yates, Yates Environmental Services, United States, 2019. Available at: https://www.adroitmarketresearch.com/industry-reports/water-desalination-market (accessed March 22, 2021)

[3] M. Hindiyeh, A. Albatayneh, R. Altarawneh, M. Jaradat, M. Al-Omary, Q. Abdelal, T. Tayara, O. Khalil, A. Juaidi, R. Abdallah, P. Dutournié, M. Jeguirim, Sea level rise mitigation by global sea water desalination using renewable-energy-powered plants, Sustainability, 13 (2021) 9552, doi: 10.3390/su13179552.

[4] GWI, Desalination Plant of the Year, Thermal Desalination is Not Dead, Global Water Intelligence, United Kingdom, 2021.

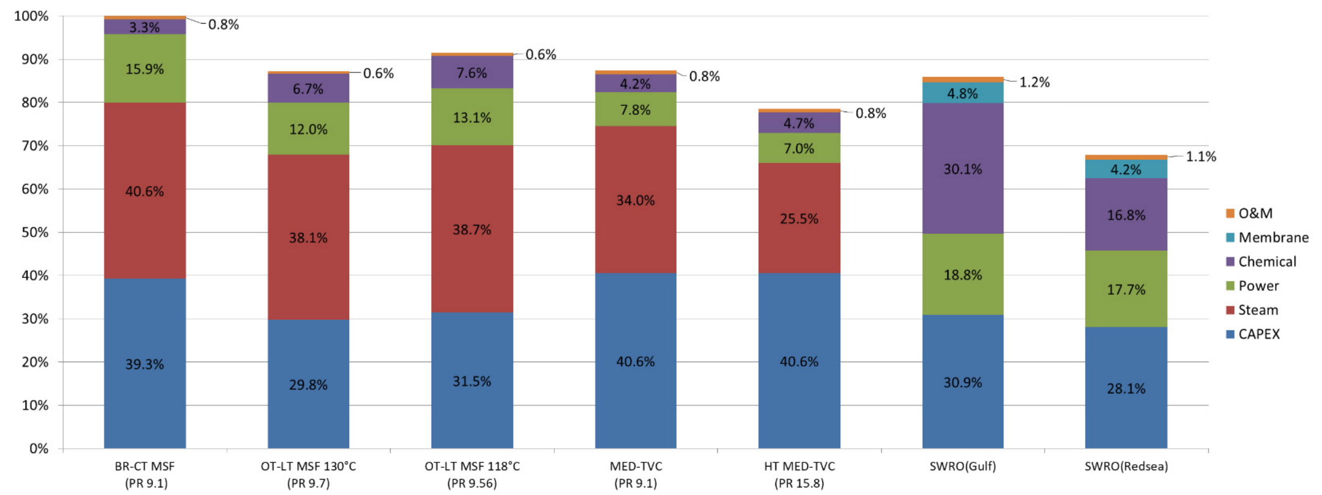

Fig. 11. Comparison of water unit cost break down for different desalination technologies .

Available at: https://www.globalwaterintel.com/news/2021/14/interpreting-the-2021-global-water-awards (accessed April 14, 2021)

[5] S. Jamaly, N.N. Darwish, I. Ahmed, S.W. Hasan, A short review on reverse osmosis pretreatment technologies, Desalination, 354 (204) 30–38.

[6] A.M. Mahmoud, Y. Kim, R.B. Mansour, A. Al-Aithan, Y. Lee, S. Ahmed, H. Varshney, H. Chung, K. Bamardouf, O.A. Hamed, A. Al-Ghamdi, F.A. Abu Derman, Experimental analysis and techno-economic study of once through long tube MSF desalination plants, Desal. Water Treat., 73 (2017) 137–144.

[7] I.S. Al-Mutaz, Features of multi-effect evaporation desalination plants, Desal. Water Treat., 54 (2015) 3227–3235.

[8] I.S. Al-Mutaz, I. Wazeer, Current status and future directions of MED-TVC desalination technology, Desal. Water Treat., 55 (2015) 1–9.

[9] I.S. Al-Mutaz, I. Wazeer, Comparative performance evaluation of conventional multi-effect evaporation desalination processes, App. Therm. Eng., 73 (2014) 1194–1203.

[10] C. Sommariva, Desalination Management and Economics, Faversham House Group, Faversham House Limited, United Kingdom, 2004.

[11] N.M. Al-Najem, M.A. Darwish, F.A. Youssef, Thermovapor compression desalters: energy and availability — analysis of single- and multi-effect systems, Desalination, 110 (1997) 223–238.

[12] S. Ihm, O.Y. Al-Najdi, O.A. Hamed, G. Jun, H. Chung, Energy cost comparison between MSF, MED and SWRO: case studies for dual purpose plants, Desalination, 397 (2016) 116–125.

[13] M.A. Saroosh, S. Ahmed, O.A. Hamed, K.A. Al-Shail, S. Ihm, H. Chung, A.S. Al-Ghamdi, F.A. Abu-Derman, Techno-Economic Evaluation of Concentrated Solar Thermal (Heat Only) Assisted Satellite MED-TVC, IDA World Congress, San Diego, USA, 2015.

[14] K. Bourouni, S. Ihm, F. Rezazadeh, A. Nafey, J.K. Park, Analysis of Scale in High Temperature MED Distiller, IDA World Congress, Perth, Western Australia, 2011.

[15] S. Ihm, K. Bourouni, C. Siklawi, M.A. Saroosh, A. Nafey, J. Choi, J. Park, Optimization of Large-Scale High Temperature MED-TVC Systems: Numerical & Experimental Verification, IWA World Water Congress & Exhibition, Busan, Korea, 2013.

[16] U.S. EPA, Method 6010D (SW-846), Inductively Coupled Plasma-Atomic Emission Spectrometry, Revision 4, Washington DC, USA, 2014.

[17] Y. Lee, O.A. Hamed, A.M. Mahmoud, K. Bamardouf, S. Ahmed, B. Park, A.S. Al-Jamhan, A demonstration of high temperature MED-TVC desalination technology in the Gulf Area, Am. J. Chem. Eng., 7 (2019) 57–64.

[18] K.A. Khalid, M.A. Antar, A. Khalifa, O.A. Hamed, Allocation of thermal vapour compressor in multi effect desalination systems with different feed configurations, Desalination, 426 (2018) 164–173.

[19] O.A. Hamed, M.N. Al-Ghannam, K.A. Al-Shail, A.M. Farooque, R. Al-Rasheed, S. Al-Fozan, A.R. Al-Arifi, M. Hirai, Y. Taniguchi, S. Araki, K. Harada, K. Maekawa, Successful Operation of MED/TVC Desalination Process at TBT of 125°C Without Scaling, IDA World Congress, REF: IDAWC/DB09-062, Atlantis, The Palm – Dubai, UAE, 2009.

[20] M. Luo S. Wang, J. Yang, The scaling preventable measures of multi-effect distillation plants, Adv. Mater. Res., 955–959 (2014) 605–609.

[21] A.Y. Abdulgader, G.M. Mustafa, N. Nada, K. Al-Hasani, Performance Evaluation of Belgard EV2050 at Al-Aziziah Reheat Plant, Technical Report No. TR-3808/EVP96004, Saline Water Conversion Corporation, Saudi Arabia, 1998, pp. 1786–1804.

[22] O. Hamed, A.M. Mahmoud, K. Bamardouf, A. Al Ghamdi, A. Al-Hamzah, Thermal performance of MED-TVC pilot at 95°C elevated temperature with acid-anti-scalant blend treatment, Int. J. Mech. Eng. Appl., 9 (2021) 15–18.

[23] G. Ozair, K.Z. Al-Sebaie, S.A. Al-Zahrany, H.S. Al-Subhi, Y.A. Abuayed, Dynamic Simulation and Thermodynamic Assessment of the High Performance MED-TVC Plant at Marafiq-Yanbu, IDA World Congress, Sao Paulo, Brazil, 2017.

[24] M. Matar, Cost Effective – High-Performance Antiscalant 'ALBRIVAP® DSB (M) A' in MSF Units, The 12th Gulf Water Conference, Water Sciences and Technology Association, Bahrain, 2017.

[25] Adding Cost Breakdown for MED Global Water Intelligence, United Kingdom, Vol. 11, Issue 9, Sep. 2010, p. 8.