

# Boron evaporation in thermally-driven seawater desalination: Effect of temperature and operating conditions

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## Appendices

**Reagents:** Analytical grade  $H_3BO_3$ , sodium hydroxide (NaOH), nitric acid ( $HNO_3$ ) and UCON™ THF 14 heating bath oil were purchased from Sigma-Aldrich (St. Louis, MO, USA). The Milli-Q water was generated by a Milli-Q Ultrapure Water System (Millipore Corp., Bedford, MA, USA). Red Sea water was collected from the sea intake pipe.

**Glassware cleaning:** All the glass parts of the Rotovapor® system were soaked in 1 M  $HNO_3$  for 30 min followed by rinsing with Milli-Q water and air-drying to prevent any cross-contamination of distillate samples from boron which might remain on the glass walls from the previous evaporation experiments. To ensure that boron was not leaching from the glassware, two additional tests were performed. In the first test, all glassware parts were soaked individually in the Milli-Q water for 72 h, and boron concentration in this water was measured by the Inductively Coupled Plasma Mass Spectrometer (ICP-MS). In the second test, Milli-Q water was evaporated in the Rotovapor® system at the highest evaporation temperature of 104 °C. Distillate water was further collected and analyzed for boron content. No boron was detected in any sample from both tests confirming no boron leaching from the glassware. Therefore, it was assumed that all the boron measured in the actual distillate water samples, has originated from the evaporation of seawater or boric acid solution.

**Bench-scale evaporation experiments:** The vapor duct and evaporating flask were connected through a 15 cm glass connector filled with a stainless steel demister to prevent carry over of droplets. A 500 mL round bottom evaporating flask was filled with 255 g of seawater or boric acid solution. The boiling temperatures were monitored with the mercury-in-glass thermometer immersed in the flask through the hole in neoprene rubber stopper.

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33 **The detection limit of boron** was 0.1 µg/L and the calibration curve was linear in the range of 1  
34 µg/L – 100 µg/L with the coefficients of regression  $R^2$  being > 0.99 during the entire period of  
35 measurements.

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37 **Virgin membrane conditioning:** The AGMD process with Milli-Q water was conducted for 1 h  
38 at 70°C to wash out the residual solvents originated from membrane casting process. A new  
39 membrane coupon was used for each AGMD run.

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41 **The effect of feed temperature on vapor flux and boron rejection in the temperature-**  
42 **dependent AGMD process:** The effect of feed temperature on water vapor flux and boron  
43 rejection in the AGMD process was studied in a feed temperature range of 65°C – 80°C and at a  
44 constant coolant temperature of 18°C. The volume of the feed was 8 L. A weight of permeate  
45 which accumulated for one hour at each feed temperature was recorded and further used to  
46 calculate the AGMD vapor flux according to equation A.2.

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48 **AGMD concentrating mode conditions:** The initial volume of the feed in both cases was 4.125  
49 L, and each experiment was conducted for 21 h at 18 °C and 80 °C of coolant and feed  
50 temperatures, respectively, to maximize water vapor flux.

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## 52 **Calculations:**

53 (1) The *in situ* pH values at different boiling temperatures were calculated according to the  
54 following equation:

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$$56 \quad pH (\text{in situ temp } t_2) = pH_{t_1} + 0.0114(t_1 - t_2) \quad (\text{A.1})$$

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57 where  $t_1$  and  $t_2$  are the ambient and *in situ* solution temperatures, respectively [29].

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59 (2) The water vapor flux ( $J$ ) and boron rejection ( $R$ ) were calculated according to equations  
60 A.2 and A.3, respectively:

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62  $J = \frac{m_W}{At}$  (A.2)

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64  $R = \left(1 - \frac{C_p}{C_f}\right) 100$  (A.3)

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66 where  $m_W$  is the permeate weight (kg),  $A$  is the membrane surface area ( $m^2$ ),  $t$  is the time (h),  
67  $C_p$  is the concentration of boron in permeate (mg/L), and  $C_f$  is the concentration of boron in feed  
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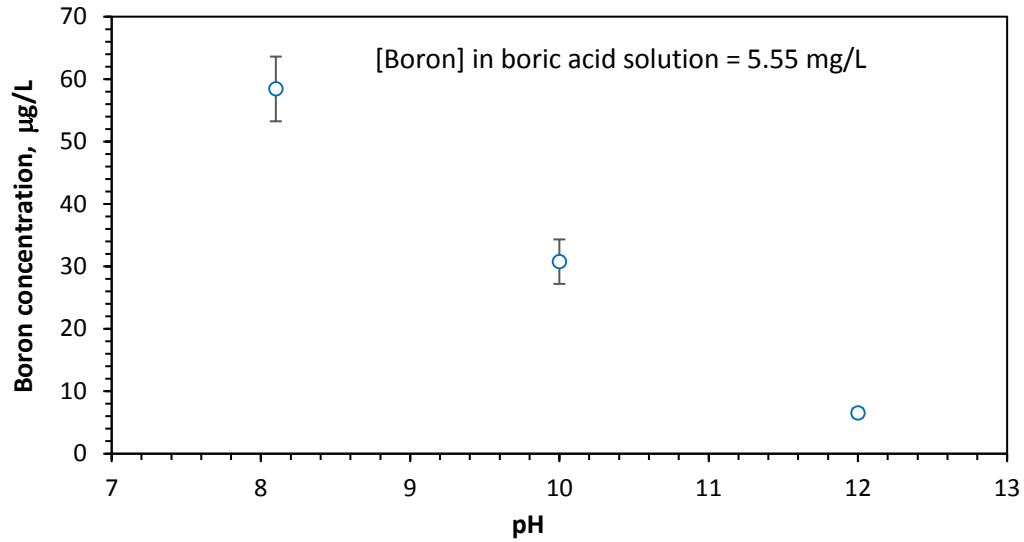
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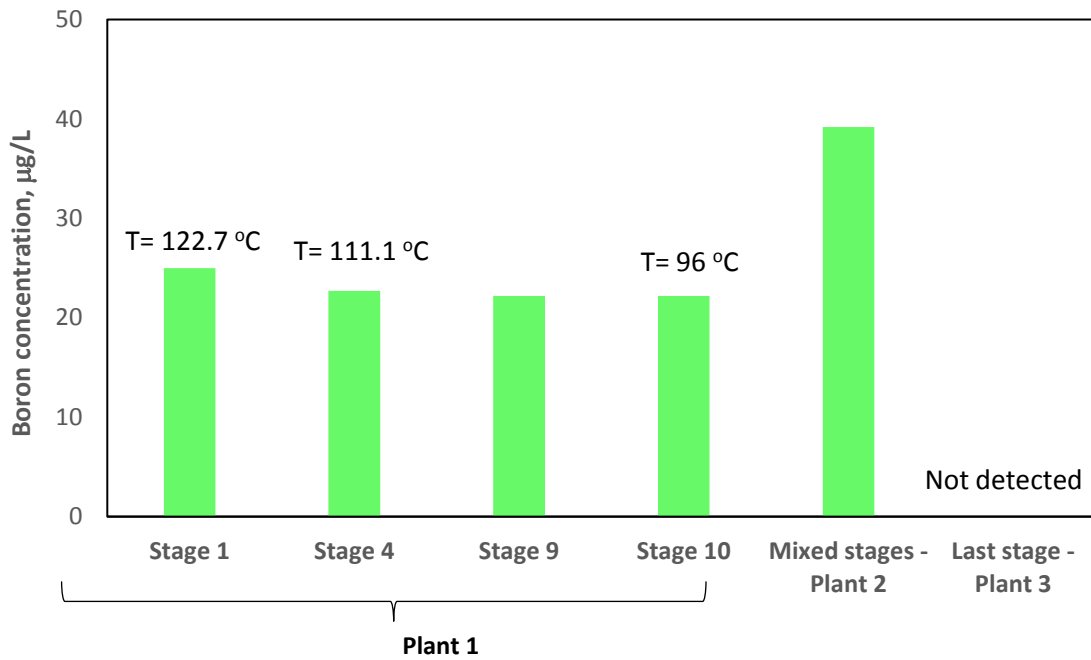
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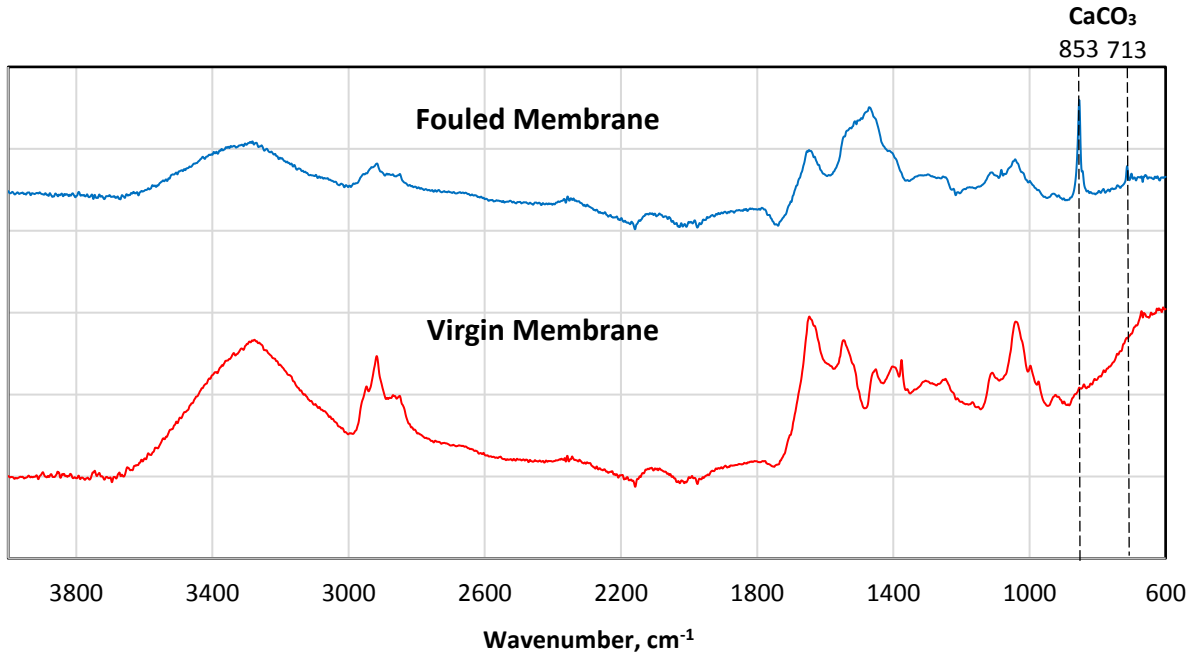
**Figure A.1.** Boron concentration in distillate samples from evaporation of boric acid solution at 104 °C at different pHs.



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**Figure A.2.** Boron concentration in distillate samples from commercial MSF plants.

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105 **Figure A.3.** ATR FT-IR spectra of virgin and fouled PVDF membranes after 21 h of seawater  
106 AGMD process.

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122 **Table A.1.** Calculated molar concentrations and molar fractions of boric acid ( $H_3BO_3$ ) and  
 123 borate ion ( $H_2BO_2^-$ ) in boric acid solution at boron concentration of 5.55 mg/L.

pH	Molar concentration, M		Molar fraction	
	$H_3BO_3$	$H_2BO_2^-$	$H_2BO_2^-$	$H_3BO_3$
pH 8.1	$47.9 \cdot 10^{-5}$	$3.5 \cdot 10^{-5}$	0.07	0.93
pH 10.0	$7.6 \cdot 10^{-5}$	$43.8 \cdot 10^{-5}$	0.85	0.15
pH 11.0	$0.9 \cdot 10^{-5}$	$51.3 \cdot 10^{-5}$	0.98	0.02
pH 12.0	$0.09 \cdot 10^{-5}$	$51.4 \cdot 10^{-5}$	0.998	0.002

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125 **Table A.2.** pH to which the boric acid solution was adjusted at 20 °C (ambient) and its  
 126 corresponding value at 104 °C (*in situ*). Concentration of boron in boric acid solution was 5.55  
 127 mg/L.

pH at 20 °C (ambient)	pH at 104 °C ( <i>in situ</i> )
8.1	7.1
10.0	9.0
12.0	11.0

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129 **Table A.3.** Process parameters and water quality of the distillate samples collected from  
 130 different commercial MSF plants.

Stage	Brine temperature, °C	Process pressure, kPa	Conductivity, $\mu S/cm$	Boron, $\mu g/L$
MSF Plant #1 (Arabian Gulf Coast)				
Stage 1	122.7	1.35	11.1	24.96
Stage 4	111.1	0.49	14.3	22.74
Stage 9	-	-	20.8	22.15
Stage 10	96.0	0.18	27.2	22.19
MSF Plant #2 (Red Sea Coast)				
Mixed stages	-	-	-	39.18
MSF Plant #3 (Red Sea Coast)				
Last stage	45-.0	-	5.7	Non detected

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135 **Table A.4.** Water quality of distillate samples of Red Sea water bench-scale distillation  
 136 experiments.

Temperature, °C	pH	Conductivity, $\mu\text{S/cm}$
55	$5.8 \pm 0.1$	$9.0 \pm 2.1$
65	$5.8 \pm 0.2$	$8.0 \pm 2.8$
70	$5.9 \pm 0.1$	$11.0 \pm 5.7$
75	$5.7 \pm 0.1$	$9.5 \pm 4.9$
80	$5.9 \pm 0.3$	$9.7 \pm 1.4$
90	$5.9 \pm 0.3$	$8.2 \pm 4.2$
104	$5.6 \pm 0.1$	$10.2 \pm 2.1$

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138 **Table A.5.** Quality of Res Sea water permeate collected during the AGMD process at different  
 139 feed temperatures.

Feed temperature, °C	pH	Conductivity, $\mu\text{S/cm}$
65.5	5.9	75.4
70.4	5.9	55.5
75.5	6.0	43.3
80.5	5.9	43.8

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141 **Table A.6.** Quality of permeate collected at different times during 21 h of the AGMD process.

Time, h	pH	Conductivity, $\mu\text{S/cm}$
0	5.9	135.8
3	5.9	146.2
5	5.8	136.3
10	6.1	262.6
21	6.0	223.7

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