THERMAL DESALINATION PROCESSES AND ECONOMICS

A 4-day intensive course

Lecturer Dr. Corrado Sommariva

23–26 July 2007
L’Aquila, Italy

Courtesy of Corrado Sommariva. Used with permission.
Future Directions in Integration of Desalination, Energy and the Environment

Leon Awerbuch,
President of Leading Edge Technologies,
Director of IDA

A seminar sponsored by
American Nuclear Society - Student Chapter
and
Department of Nuclear Science and Engineering
Massachusetts Institute of Technology
Boston, February 23rd, 2009

Courtesy of Leon Awerbuch. Used with permission.
Thus the heat is “recycled” within the system. Energy efficiency is a function of the number of effects.
The concept of thermo compression
If reduced pressure causes evaporation at a lower temperature, then compression should force condensation at a higher temperature.
The combination of these phenomena can yield useful (and efficient) desalination process.

MED desalination plant

Typical stage arrangement of a large MED plant

Courtesy of Corrado Sommariva. Used with permission.
Multi-Effect Distillation (MED)

Raw seawater total dissolved solids (TDS): 35-47,000 mg/L
Top brine temperature: 63-75°C
Performance ratio: 12
Electrical power: 2 kWh/m³
Scale inhibitors used for scale control
Dual purpose plant

Unit size reached 8 MIGD in Sharjah, new design for unit sizes 10-15 MIGD

Courtesy of Leon Awerbuch. Used with permission.
MED cross flow plant internal layout

Courtesy of Corrado Sommariva. Used with permission.
# MED Key Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Capital Cost MED</td>
<td>4.5-9.0</td>
<td>US$ MM per MIGD</td>
</tr>
<tr>
<td>Capital Cost – Intake/Outfall</td>
<td>0.1-2.0</td>
<td>US$ MM per MIGD of cooling</td>
</tr>
<tr>
<td>MED GOR</td>
<td>12</td>
<td>Tons of product/ton of steam</td>
</tr>
<tr>
<td>LP Steam Supply</td>
<td>2.5-3</td>
<td>Bar A</td>
</tr>
<tr>
<td>Lost Power Potential</td>
<td>1.225</td>
<td>MW/MIGD</td>
</tr>
<tr>
<td>Power Consumption</td>
<td>1.8</td>
<td>KWh/m³ of distillate</td>
</tr>
<tr>
<td>Steam Consumption</td>
<td>15.8</td>
<td>Tons/MIGD</td>
</tr>
<tr>
<td>Chemical Costs</td>
<td>40,000</td>
<td>US$/yr per MIGD</td>
</tr>
<tr>
<td>MED R&amp;R</td>
<td>1%</td>
<td>TIC/yr</td>
</tr>
<tr>
<td>Labor</td>
<td>40,000</td>
<td>US$/yr per MIGD</td>
</tr>
</tbody>
</table>

Courtesy of Leon Awerbuch. Used with permission.
MED arrangements

TYPICAL HTE ARRANGEMENT

TYPICAL VTE ARRANGEMENT

Courtesy of Corrado Sommariva. Used with permission.
Desalination projects: MED layout

Courtesy of Corrado Sommariva. Used with permission.
**Multiple effect desalination**

Evolved from small installation

*Courtesy of Corrado Sommariva. Used with permission.*

to relatively large unit size

*With thermo compression*

*Courtesy of Corrado Sommariva. Used with permission.*

*Condesing*
One of more efficient MED plants with Performance Ratio of 12 in Las Palmas

Courtesy of Leon Awerbuch. Used with permission.
The concept of thermo compression

If reduced pressure causes evaporation at a lower temperature, then compression should force condensation at a higher temperature.

The combination of these phenomena can yield useful (and efficient) desalination process.

ΔT pitch

Courtesy of Corrado Sommariva. Used with permission.
Flow sheets: Once through

Steam Supply

Thermo Compressor

Ejectors

Ejector Condensers

Vent

Feed

Condensate Return

First effect

Second effect

Third effect

Last effect

Final Condenser

Seawater

To Product Water Treatment

Brine

Cooling Water Discharge

Strainers

Courtesy of Corrado Sommariva. Used with permission.
Fluid flowing in the pipeline (the “motive fluid”) speeds up to pass through the restriction and in accordance with Bernoulli’s equation creates vacuum in the restriction.

A side port at the restriction allows the vacuum to draw a second fluid (the “ejected”) into the motive fluid through the port.

Turbulence downstream of the port entrains and mixes the ejected into the motive fluid.
The MED unit 22,700 m³/d in operation over five years at Layyah Power Desalination in Sharjah

Courtesy of Leon Awerbuch. Used with permission.
Schematic of multiple effect evaporation with vapor compression (A) parallel feed thermal vapor compression, (MEE-P/TVC) and (B) parallel feed mechanical vapor compression, (MEE-P/MVC).

Figure by MIT OpenCourseWare. Adapted from Fig. 1 in El-Dessouky, H. T., and H. M. Ettouney. "Multiple Effect Evaporation - Vapor Compression." Chapter 5 in Fundamentals of Salt Water Desalination. New York, NY: Elsevier, 2002.
MSF desalination plant

Typical stage arrangement of a large MSF plant

Stage modeling thermodynamic ideal case

Courtesy of Corrado Sommariva. Used with permission.
Process description: How did it begin?

- It had long been known that water could be heated above its normal boiling point in a pressurized system.
- If the pressure was released, a portion of the water would boil off or “flash”. The remaining liquid water would be cooled as the issuing vapor took with it its heat of vaporization.
- Since evaporation occurred from the bulk fluid rather than at a hot heat exchange surface, opportunities for scaling would be reduced.

What flashing looks like

- Hot brine from the previous stage enters through slot at lower temperature and pressure stage
- It senses the new lower pressure environment, and
- Flashes!

Courtesy of Corrado Sommariva. Used with permission.
MSF desalination plant

MSF what process?

Courtesy of Corrado Sommariva. Used with permission.
Multistage Flash (MSF)

Raw seawater total dissolved solids (TDS):
35-47,000 mg/L

Top brine temperature: 100-112°C

Performance ratio: 8

Electrical power: 3-4 kWh/m³

Scale inhibitors used for scale control

Recycle type plant

Dual purpose plant

Unit size 16.7-20 MIGD

Courtesy of Leon Awerbuch. Used with permission.
Energy effect

In fact, as it can be seen from the energy flow diagram below, the great part of the heat input to the MSF system is returned back to the sea with the seawater drain stream.

Courtesy of Corrado Sommariva. Used with permission.
## MSF KEY PARAMETERS

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Capital Cost MSF</td>
<td>5.5-10 US$ MM per MIGD</td>
</tr>
<tr>
<td>Capital Cost – Intake / Outfall</td>
<td>0.1-2.0 US$ MM per MIGD of cooling</td>
</tr>
<tr>
<td>MSF GOR</td>
<td>8 Tons of product/ton of steam</td>
</tr>
<tr>
<td>LP Steam Supply</td>
<td>2.5-3 Bar. A</td>
</tr>
<tr>
<td>Lost Power Potential</td>
<td>1.225 MW/MIGD</td>
</tr>
<tr>
<td>Power Consumption</td>
<td>4 kWhr/m³ of distillate</td>
</tr>
<tr>
<td>Steam Consumption</td>
<td>23.7 Tons/MIGD</td>
</tr>
<tr>
<td>Chemical Costs</td>
<td>40,000 US$/yr per MIGD</td>
</tr>
<tr>
<td>MSF R&amp;R</td>
<td>1% TIC/yr</td>
</tr>
<tr>
<td>Labor</td>
<td>40,000 US$/yr per MIGD</td>
</tr>
</tbody>
</table>

Courtesy of Leon Awerbuch. Used with permission.
Multi stage flash — dominant technology world-wide

Cross-tube and long-tube MSF distillers

Courtesy of Corrado Sommariva. Used with permission.
Multi stage flash

Long tube distillers:
we need to distinguish between the stages and the passes
MSF long flow plant internal layout

Sectional View of Evaporator Module

Courtesy of Corrado Sommariva. Used with permission.
THE JEBEL ALI K2 INSTALLATION

40 MIGD + 800 MW

3 * 13.33 MIGD
p.r. 8.0 – 8.5 kg/2326 kJ

Courtesy of Leon Awerbuch. Used with permission.
THE SHUWEIHAT INSTALLATION

100 MIGD + 1500 MW

6 * 16.7 MIGD
P.R. 9.0 kg/2326 kJ

Drain cooler

Courtesy of Leon Awerbuch. Used with permission.
Interfaces with the rest of the plant
Typical layout

Courtesy of Corrado Sommariva. Used with permission.
Typical layout

Seawater intake
Chlorination building

Power yard

Courtesy of Corrado Sommariva. Used with permission.
MSF cross flow plant internal layout

How it really looks like - low side flash chamber

Courtesy of Corrado Sommariva. Used with permission.
How it really looks like - upper side

Tube bundle tube supports roof plates and incondensable extraction pipes

Details of tube bundle and tube support

Courtesy of Corrado Sommariva. Used with permission.

Distillate tray, demister supports and interstage walls

Courtesy of Corrado Sommariva. Used with permission.
MSF long flow plant internal layout: how it really looks like

Courtesy of Corrado Sommariva. Used with permission.
Improvements in distillation processes

TOP BRINE TEMPERATURE: The Increase of TBT can Allow Higher Production With Almost Same Desal Trains

HYBRIDIZATION: The Application Of Hybrid Technologies (MSF + RO+NF, or MSF+RO+NF + MED) Can Improve Overall Efficiency

THERMAL IMPROVEMENT: Better HTC, new materials, New MSF+MED Schemes And Ancillary Equipment.

Courtesy of Leon Awerbuch. Used with permission.
Potential for MED technology improvements

• Increasing TBT from 63°C to 80-100°C with Nanofiltration

• Increase efficiency to PR 12-16 from current 9.

• Increase unit size to 15 MIGD from current 8 MIGD

• Improve HTC by oval and corrugated plates

• Hybridize with MSF-RO-NF

Courtesy of Leon Awerbuch. Used with permission.
Example of hybrid system components and their relations.

Courtesy of Leon Awerbuch. Used with permission.
Past Simple hybrid

Product waters from the RO and Distillation plants are blended to obtain suitable product.

Power to water ratio can be significantly reduced.

GOING TO THE NEXT STEP

A single stage RO process can be used. Higher Recovery lower pretreatment

Courtesy of Leon Awerbuch. Used with permission.
The feedwater temp. to the RO plant is optimized using cooling water from the heat-reject section of the MSF/MED or power plant condenser. Constant feed temperature

The low-pressure steam from the MSF/MED plant is used to de-aerate or use de-aerated brine as a feedwater to the RO plant to minimize corrosion and reduce residual chlorine.

Courtesy of Leon Awerbuch. Used with permission.
Integrated hybrid

- Blending distillate and membrane permeate will reduce requirements on Boron removal by RO.

The RO and NF membrane life can be extended. (12 years)

Courtesy of Leon Awerbuch. Used with permission.
Integrated hybrid environmental benefits

Cool RO Reject and Feed to be used as a cooling source for heat reject section of distillation plants.

The blend of reject stream from RO with warm seawater and blowdown from distillation or power plants reduces heavy density plume of RO outfall.

Blend of RO permeate reduces temperature of distillate.

A common, smaller seawater intake & outfall.

Courtesy of Leon Awerbuch. Used with permission.
The Fujairah1 plant due to hybridization generates only 500 MW net electricity for export to the grid, and 662 MW gross for water production capacity of 100 MIGD. Otherwise similar MSF only plant in Shuweihat required 1500 MW for the same 100 MIGD capacity. The Fujairah desalination plant is split into 62.5 MIGD from the thermal part and 37.5 MIGD from the membrane process.

Fujeirah 2 will be 100 MIGD MED and 30 MIGD RO

Courtesy of Leon Awerbuch. Used with permission.
Fujairah Plant - Power Desalination Hybrid

Courtesy of Leon Awerbuch. Used with permission.
Benefits of Nanofiltration

PREFERENTIALLY REMOVES SCALING (DIVALENT) IONS

ALLOWS HIGHER TOP BRINE TEMPERATURE FOR MSF (121 vs. 105 °C)

Higher Flash Range Increases Production

Reduced MSF Capital Costs

Reduced MSF Operating Costs

Courtesy of Leon Awerbuch. Used with permission.
HYBRID WITH NF PRIOR TO MSF

Courtesy of Leon Awerbuch. Used with permission.
## Energy Requirements (Steam/Electricity)

<table>
<thead>
<tr>
<th>Product</th>
<th>Process Live Steam (ton product/ton steam)</th>
<th>Electricity kWhr/ton</th>
</tr>
</thead>
<tbody>
<tr>
<td>Multi Stage Flash</td>
<td>8</td>
<td>4</td>
</tr>
<tr>
<td>Vapour Compression</td>
<td>n/a</td>
<td>8</td>
</tr>
<tr>
<td>Multi Effect Distillation</td>
<td>12</td>
<td>2</td>
</tr>
<tr>
<td>Reverse Osmosis:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>with energy recovery</td>
<td>n/a</td>
<td>3.5-5.5</td>
</tr>
<tr>
<td>without energy recovery</td>
<td>n/a</td>
<td>8.5</td>
</tr>
</tbody>
</table>

Courtesy of Leon Awerbuch. Used with permission.
## Energy Requirements for Desalination

<table>
<thead>
<tr>
<th>Process/energy type</th>
<th>MED</th>
<th>MED - TVC</th>
<th>MSF</th>
<th>VC</th>
<th>RO</th>
</tr>
</thead>
<tbody>
<tr>
<td>Steam pressure, ata</td>
<td>0.2 - 0.4</td>
<td>2.5-3.5</td>
<td>2.5-3.5</td>
<td>_</td>
<td>_</td>
</tr>
<tr>
<td>Electric energy equivalent, kWhr/m³</td>
<td>4.5</td>
<td>9.5-11*</td>
<td>9.5-11.0</td>
<td>_</td>
<td>_</td>
</tr>
<tr>
<td>Electric consumption, kWhr/m³</td>
<td>1.2--1.8</td>
<td>1.2--1.8</td>
<td>3.2-4.0</td>
<td>8.5</td>
<td>3.5-5.0</td>
</tr>
<tr>
<td>Total electric energy equivalent, kWhr/m³</td>
<td>5.2-6.3</td>
<td>10.7-12.8</td>
<td>12.7-15</td>
<td>8.5</td>
<td>3.5-5.0</td>
</tr>
</tbody>
</table>

Courtesy of Leon Awerbuch. Used with permission.
Power Generation Technologies

Back-pressure Steam Turbines
Extraction Steam Turbines
Gas Turbines
Combined Cycle Plants
Nuclear Energy
Alternative Energy
  - Solar, Wind, Geothermal, OTEC, Tide, Wave, Biofuel, PRO-Forward Osmosis

Courtesy of Leon Awerbuch. Used with permission.
# Typical Power to Water Ratios for Different Technologies

<table>
<thead>
<tr>
<th>Technology</th>
<th>PWR (MW required/Million Imperial Gallons per day)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Steam Turbine BTG - MSF</td>
<td>PWR = 5.0</td>
</tr>
<tr>
<td>Steam Turbine EST - MED</td>
<td>PWR = 7.0</td>
</tr>
<tr>
<td>Steam Turbine EST - MSF</td>
<td>PWR = 10.0</td>
</tr>
<tr>
<td>Gas Turbine GT - HRSG - MED</td>
<td>PWR = 6.0</td>
</tr>
<tr>
<td>Gas Turbine GT - HRSF - MSF</td>
<td>PWR = 8.0</td>
</tr>
<tr>
<td>Combined Cycle BTG - MED</td>
<td>PWR = 10.0</td>
</tr>
<tr>
<td>Combined Cycle BTG - MSF</td>
<td>PWR = 16.0</td>
</tr>
<tr>
<td>Combined Cycle EST - MED</td>
<td>PWR = 12.0</td>
</tr>
<tr>
<td>Combined Cycle EST - MSF</td>
<td>PWR = 19.0</td>
</tr>
<tr>
<td>Reverse Osmosis RO</td>
<td>PWR = 0.8-1.5</td>
</tr>
</tbody>
</table>

Courtesy of Leon Awerbuch. Used with permission.