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SFERA-III 2nd Summer School
October 5th- 6th, 2021
Almería (Spain)

Lecture:
Overview of thermal desalination processes

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- LT-MED Processes
- Increasing MED performance
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Thermal Distillation

Parameters to measure energy efficiency of thermal distillation processes:

Gain Output Ratio (G.O.R.): kg of distillate produced for every kg of steam supplied to the distillation unit

Performance Ratio (PR): kg of distillate produce for every 2326 kJ of thermal energy supplied to the distillation unit

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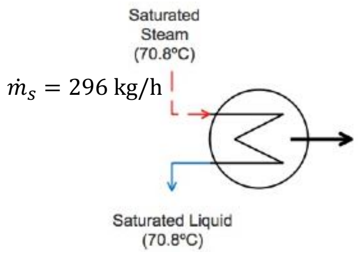
Thermal Distillation

Example: PSA SOL-14 MED Plant has a nominal production of 2984 kg/h, consuming 296 kg/h of saturated steam at 70.8˚C.

$$GOR = \frac{\dot{m}_d}{\dot{m}_s} = \frac{2984\ \mathrm{kg/h}}{296\ \mathrm{kg/h}} = 10.08$$



$$\Delta h_s(70.8°\mathrm{C}) = h_{vap,sat}(70.8°\mathrm{C}) - h_{liq,sat}(70.8°\mathrm{C}) = 2331.09\ \mathrm{kJ/kg}$$

$$PR = \frac{\dot{m}_d}{\dot{m}_s} \times \frac{\Delta h_{ref}}{\Delta h_s} = \frac{2984}{296} \times \frac{2326}{2331.09} = 10.06$$

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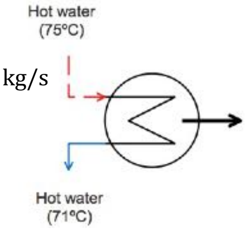
Thermal Distillation

Example: PSA SOL-14 MED Plant has a nominal production of 2984 kg/h, being powered by 12 kg/s of hot water with an inlet temperature of 75°C and an outlet temperature of 71°C.

$$\dot{m}_{hw} = 12\ \text{kg/s}$$



$$2984\ \text{kg/h} \times \frac{1\ \text{h}}{3600\ \text{s}} = 0.83\ \text{kg/s}$$

$$\dot{Q}_{hw} = \dot{m}_{hw} \times \Delta h_{hw} = 12\ \text{kg/s} \times \left(h_{hw}(75°\text{C}, 1\ \text{bar}) - h_{hw}(71°\text{C}, 1\ \text{bar})\right) = 201.13\ \text{kW}$$

$$PR = \frac{\dot{m}_d \times 2326}{\dot{Q}_{hw}} = \frac{0.83\ \text{kg/s} \times 2326\ \text{kJ/kg}}{201.13\ \text{kW}} = 9.59$$

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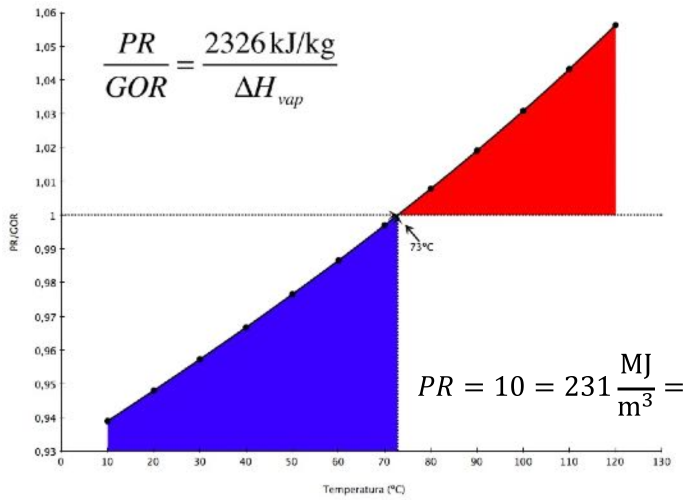
Thermal Distillation

$$\frac{PR}{GOR} = \frac{2326\,\text{kJ/kg}}{\Delta H_{vap}}$$



$$PR = 10 = 231\,\frac{\text{MJ}}{\text{m}^3} = 64.23\,\frac{\text{kWh}}{\text{m}^3}$$

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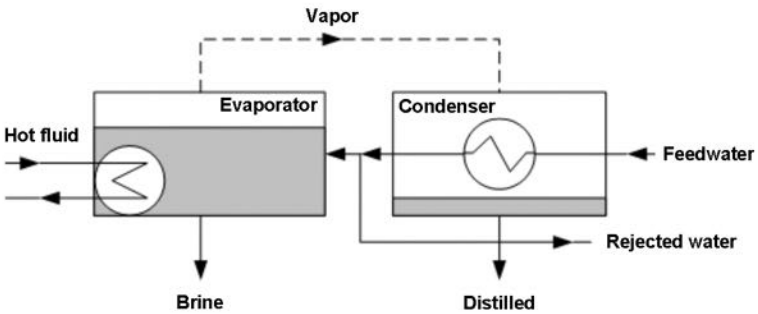
Single-effect distiller



The Performance Ratio of this thermal distillation unit has an ideal value of around 1. Most of the energy supplied to the evaporator is released to the environment in the condenser.

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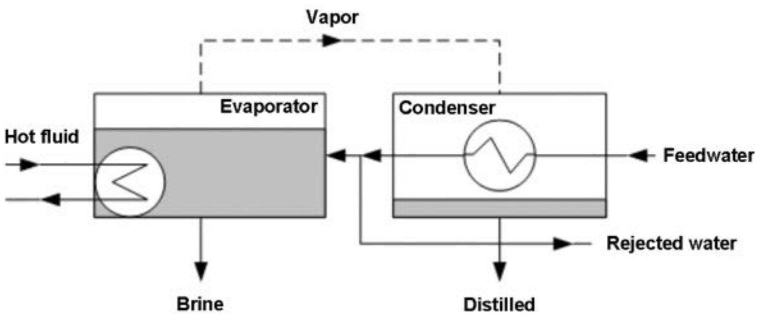
Single-effect distiller



Minimum work required for desalinate seawater (35 g/L, 25ºC) = 0.79 kWh/m^3

$$0.79\frac{kWh}{m^3} = 2.84\ \frac{MJ}{m^3}$$

$$PR = 1\ \rightarrow 2326\ MJ/m^3$$

$$\frac{2326}{2.84} = 819 \text{ times higher}$$

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Thermal Distillation

Evaporation process is very **energy demanding**

Produced **vapor must be re-condensed** to fresh water

Heat recovery is needed for an **Energy Sustainable Process**

Multiple Effect Processes
or
Multi-Stage Processes with heat recovery for pre-heating

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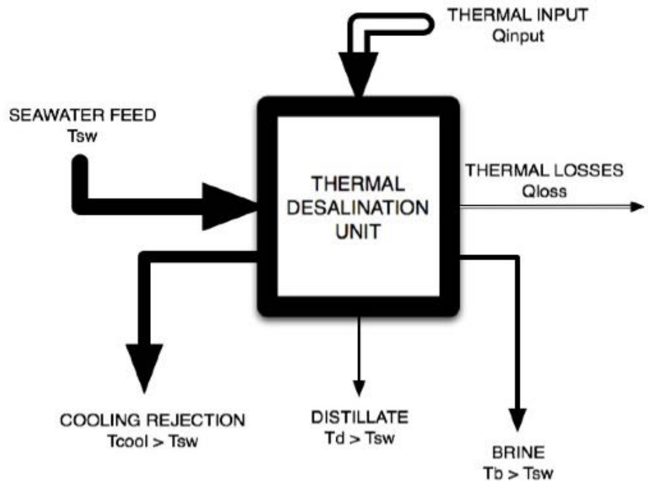
Thermal Distillation



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Thermal Distillation

- The Performance Ratio of a thermal process (without thermo- or mechanical compression) **can't be higher** than the number of evaporation/condensation processes involved.
- An increase in the thermal efficiency of the process can be achieved when temperature of the distillate, brine and cooling rejection are as near as possible to the feedwater one.
- In thermal distillation it is important to consider all the parameters: thermal energy consumption, power consumption and conversion factor. Sometimes a very good thermal performance is obtained from an unacceptable increase of the electrical consumption.

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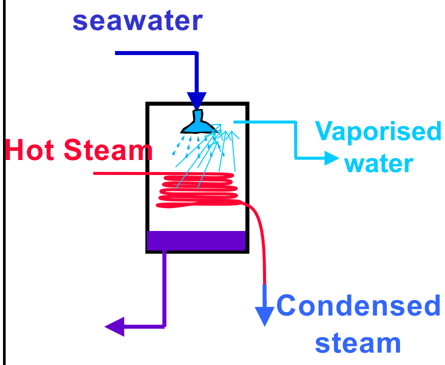
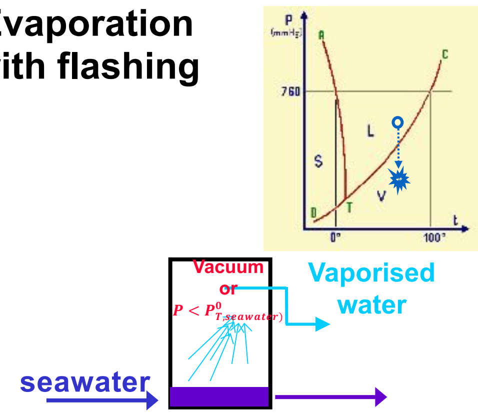
Thermal distillation

Evaporation on a hot surface



Evaporation with flashing



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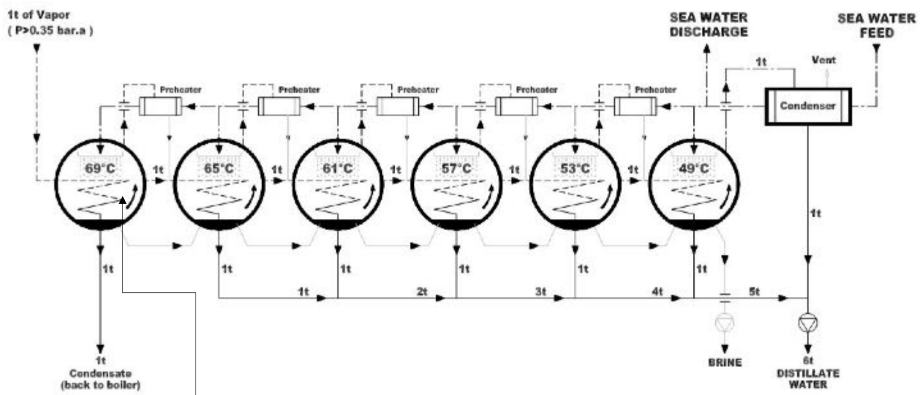
LT-MED Process



Top brine temperature: 60 - 70 ºC

Energy consumption: 2.6 kWh_e/m^3
64.0 – 78.0 kWh_t/m^3

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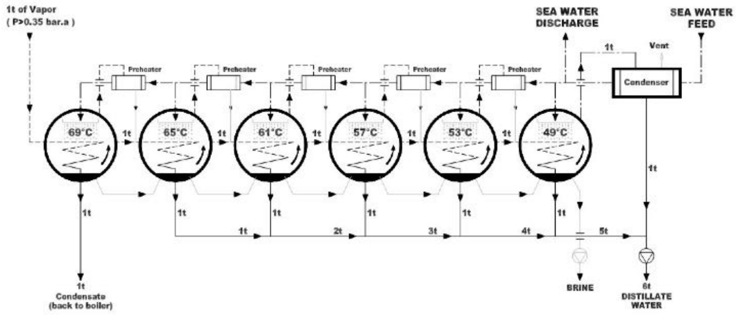
LT-MED Process



Typically, a MED plant can contain from 8 to 16 stages. They are generally implemented in units of about 2,000 to 30,000 m^3/day. The MED plants usually operate at the top brine temperatures of 70ºC in the first effect. The GOR can be as high as 12-14 and is directly related with the number of stages of the plant.

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LT-MED Process

- Different designs have been or are being used for the heat exchanger area, such as vertical tubes with falling brine film or rising liquids, horizontal tubes with falling film, or plates with a falling brine film.
- By far the most common heat exchanger used in desalination units consists of **horizontal tubes** with an external seawater **falling film**.
- Three different configurations may be used in the MEE process:
  - **Backward feed**, where the brine enters in the last stage going up to the first in counter-current with the vapor; very rarely used, due to the need of inter-stage circulating pumps (to make brine flow through the stages against a positive pressure gradient) and to the high risk of scaling in the high temperature stages (where also the salt concentration is maximum).
  - **Forward feed**, where the brine passes from one stage to the following in the same direction as the vapor;
  - **Parallel feed**, where the brine is fed equally in all the stages, (this configuration presents several advantages due to the plant simplicity and easiness of management).

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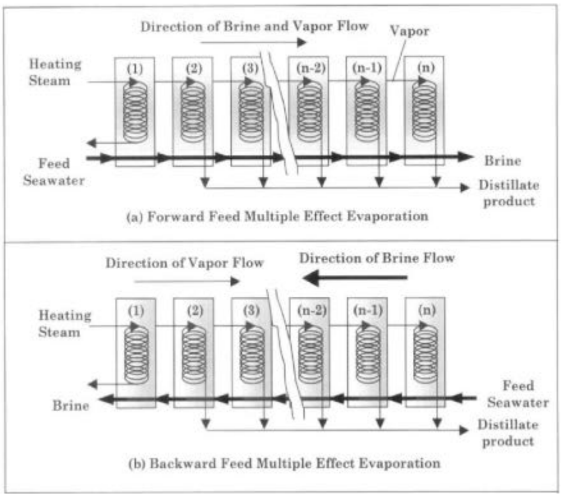
LT-MED Process



Source: El-Dessouky & Ettouney. Fundamentals of Salt Water Desalination (2002)

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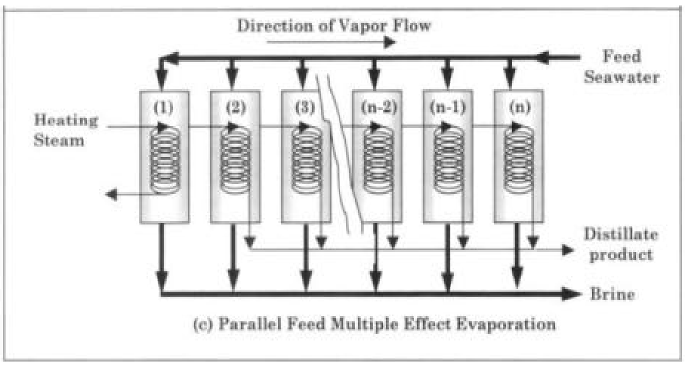
LT-MED Process



Source: El-Dessouky & Ettouney. Fundamentals of Salt Water Desalination (2002)

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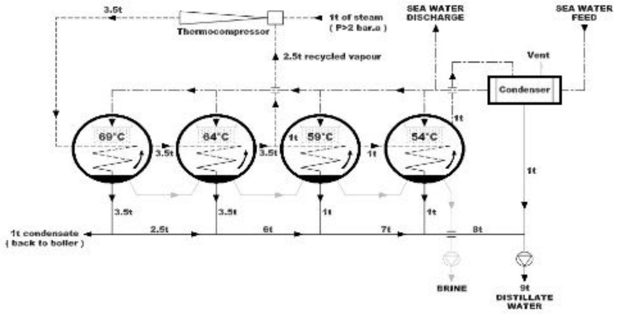
Increasing MED performance

- In order to be able to compete with technologies like reverse osmosis, MED systems need to improve their energy efficiency.
- That can be achieved by:
  - Increasing the number of effects
  - Coupling a heat pump to our MED unit to recover low-pressure heat
    - TVC-MED with steam ejectors
    - SEAHP-MED (Single effect absorption heat pump)
    - DEAHP-MED (Double effect absorption heat pump)
    - Other: MVC-MED, ADHP-MED (Adsorption heat pump)

TVC-MED Process



- In the MED process with thermocompression, part of the vapor generated in one of the effects of the MED plant is recompressed by means of a thermocompressor fed with external live steam and recycled into the tubes of the first effect of the plant.
- The effect where the thermocompressor draws the vapor is selected to optimize the plant efficiency and cost.

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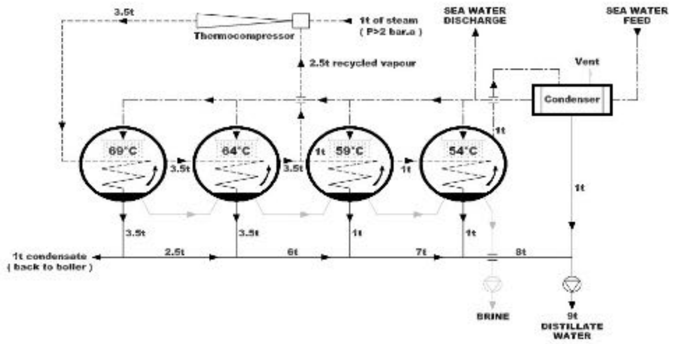
TVC-MED Process



- This system is used when steam is available at a pressure greater than 2 bar abs (2 – 40 bar abs)
- All the advantages before mentioned for the LT-MED design apply except for the unit flexibility which is slightly reduced (the unit can operate between 80 and 110% of its nominal capacity)

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TVC-MED Process

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TVC-MED Process

Nr. of effects = 6
TVC-MED a 5.3 bar(a)
G.O.R. = 9.2
Power = 0.5 kWh/m^3
Capacity = 10.000 m^3/day

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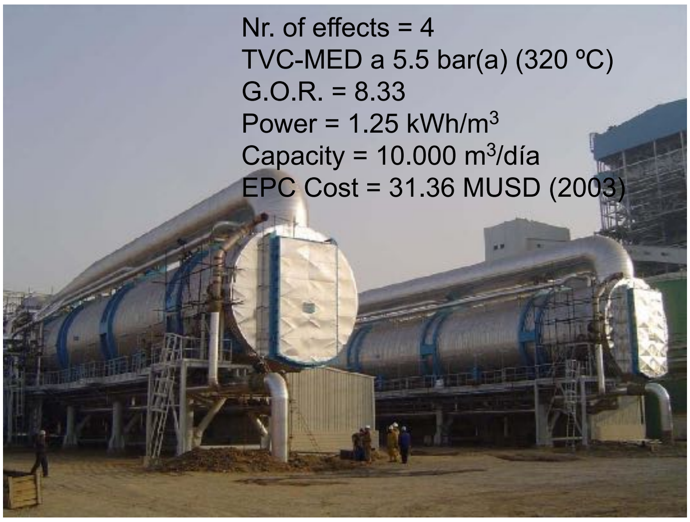
TVC-MED Process



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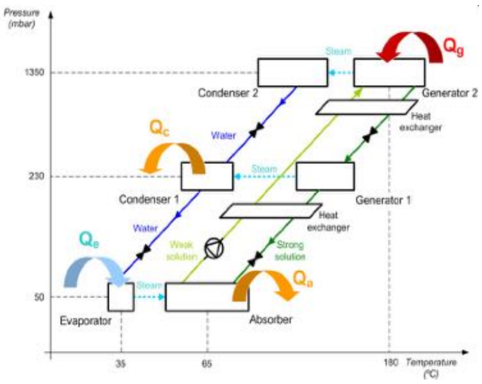
ABS-MED Process

- A way to further increasing the performance ratio is to select another type of heat pump with a higher efficiency in the operating range of a MED unit.
- Absorption heat pumps allow to upgrade low temperature heat with much higher second law efficiency than steam ejectors.
- COP (Coefficient of Performance has a different meaning than in refrigeration applications
- Single-effect (SEAHP) and double-effect absorption heat pumps can be coupled to a MED plant in order to increase the overall performance ratio



$$COP = \frac{Q_{useful}}{Q_{input}} = \frac{Q_c + Q_a}{Q_g}$$

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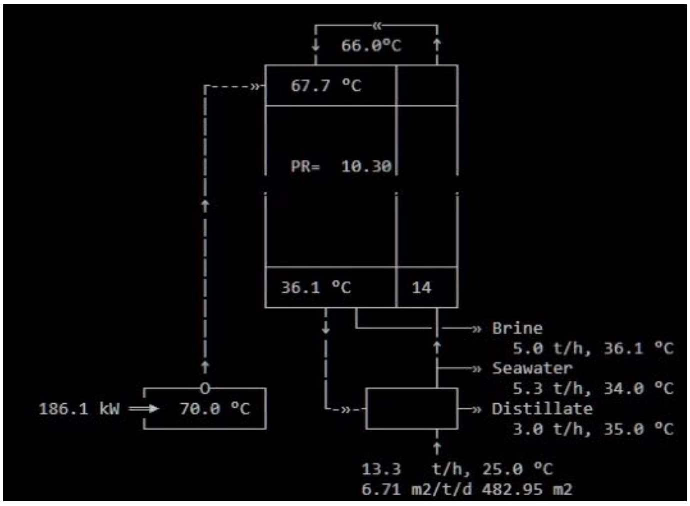
PSA SOL-14 Case Study



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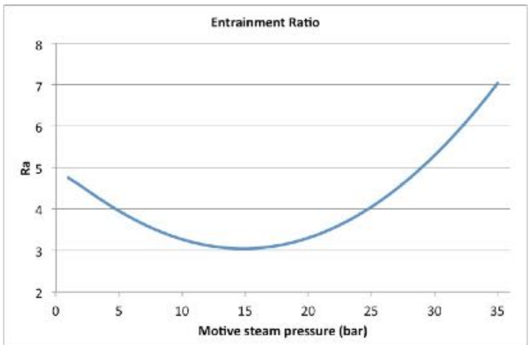
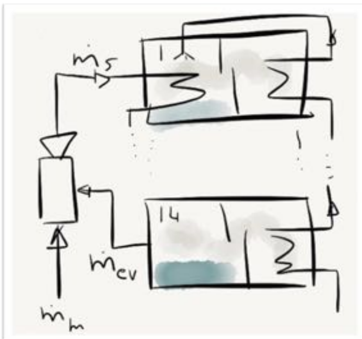
SOL-14 TVC-MED Configuration





$p_{ev} = 0.056$ bar

$p_s = 0.312$ bar

$p_m = 15$ bar

$Q_{LT-MED} = 186.1$ kW

$Ra = \frac{\dot{m}_m}{\dot{m}_{ev}} = 3.041$

$\dot{m}_m = 219.22$ kg/h $\quad \dot{m}_{ev} = 72.04$ kg/h

$COP_{TVC} = 1.57$

$PR_{TVC-MED} = PR_{LT-MED} \times COP_{TVC} = 16.17$

$Q_{TVC-MED} = 118.52$ kW

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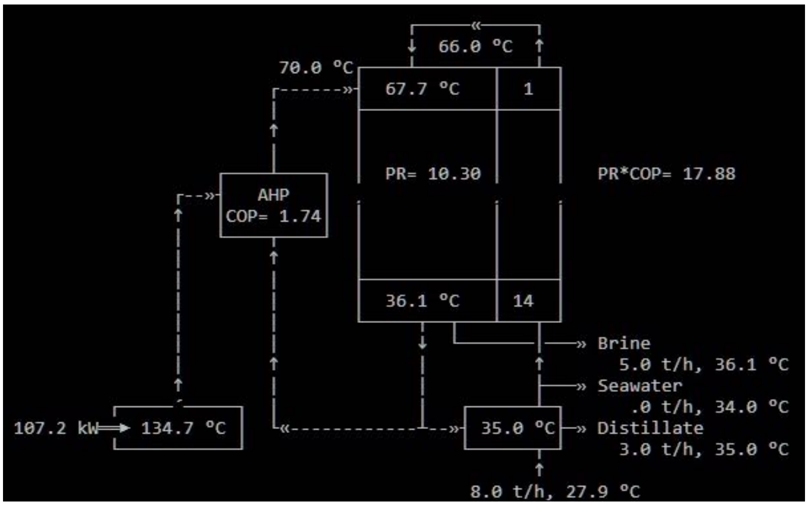
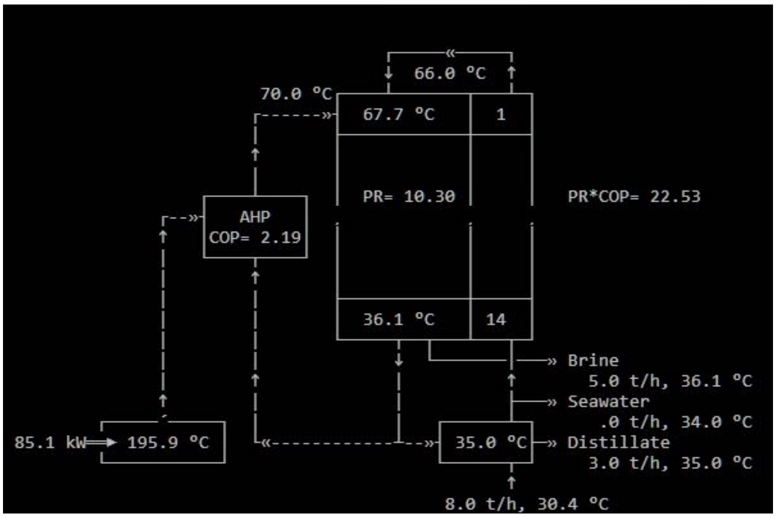
SOL-14 SEAHP-MED Configuration



SOL-14 DEAHP-MED Configuration

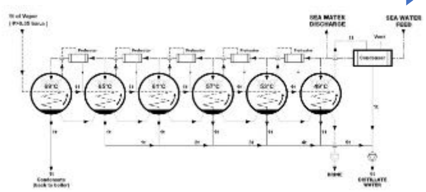


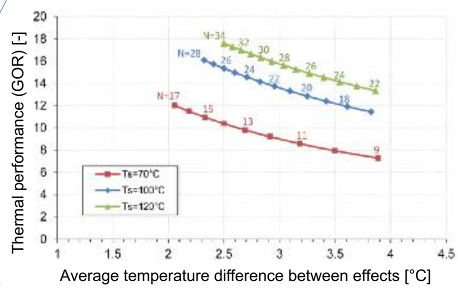
NF-MED Process

Multi-Effect Distillation with Nanofiltration (NF-MED)

- Seawater feed is pretreated with nanofiltration membranes (NF) in order to remove divalent salts.
- This allows to remove the limitation of 70ºC in the top brine temperature because scaling problems are drastically reduced.
- The use of NF pretreatment increases the specific power consumption of the desalination process.

Sea water pretreated with NF membranes





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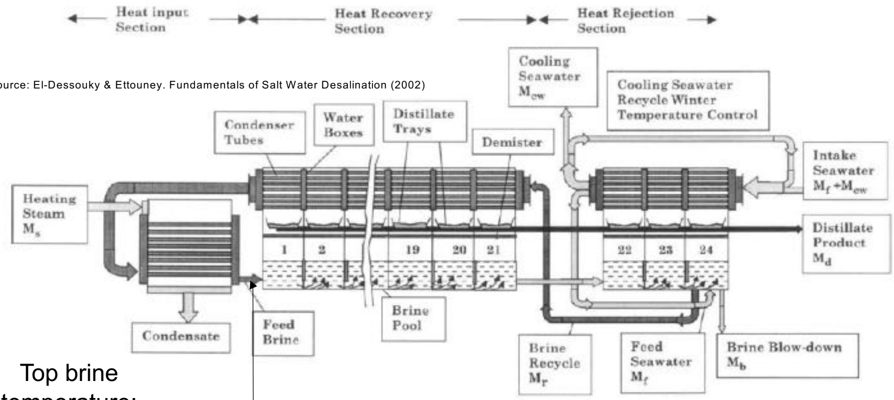
Multi-Stage Flash Evaporation (MSF)

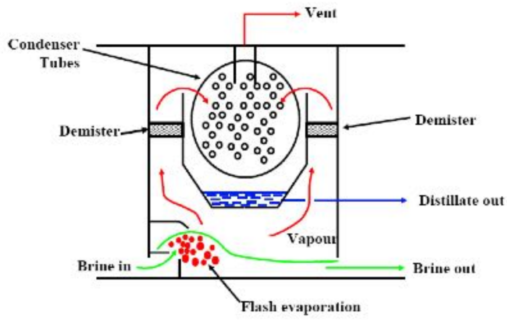
Source: El-Dessouky & Ettouney. Fundamentals of Salt Water Desalination (2002)

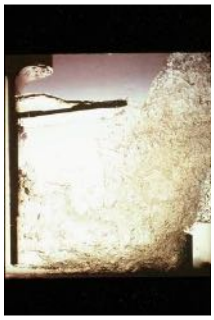


Top brine temperature: 90-120 ºC

Energy consumption: 3.75 kWh_e/m^3
79.50 kWh_t/m^3

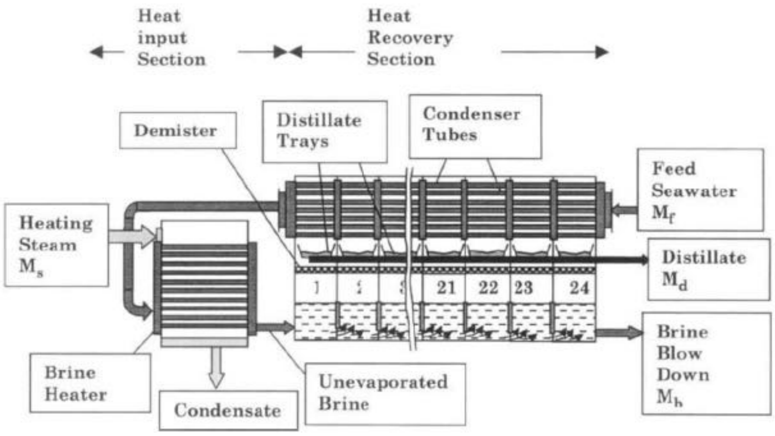
MSF Process





Typically, an MSF plant can contain from 15 to 25 stages. They are generally built in units of about 4,000 to 60,000 m3/day. The MSF plants usually operate at the top brine temperatures after the brine heater of 90-115ºC. The GOR is typically around 8-10. The thermal efficiency of the plant depends on the difference between the temperature in the last stage on the cold end of the plant and the brine heater exit (not on the number of stages).

MSF Process



Source: El-Dessouky & Ettouney. Fundamentals of Salt Water Desalination (2002)

Multistage flash desalination once through process

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MSF Process

"Once Through" MSF: comments

- In "Once Through" MSF units the plant configuration is **simpler** than in the "Brine Circulation", due to the complete absence of the heat rejection stages and of brine re-circulation in the unit.
- This makes the "Once Through" process easier to understand, but brings some **disadvantages**, which causes it not to be the best industrial choice.
- These main disadvantages are:
  1. **Unfeasible control of the brine temperature** by manipulating circulating brine flow rate, thus generating worse performances when water temperature decreases under the values at which the process was optimized (seasonal variations of seawater temperature may well be in the range 10-15°C);
  2. **Conversion Ratio** (i.e. the ratio between produced water and feed brine) **is significantly lower** than for the brine circulation configuration. Thus specific costs of seawater intake, pre-treatment and chemicals increase dramatically causing economical drawbacks to the process.

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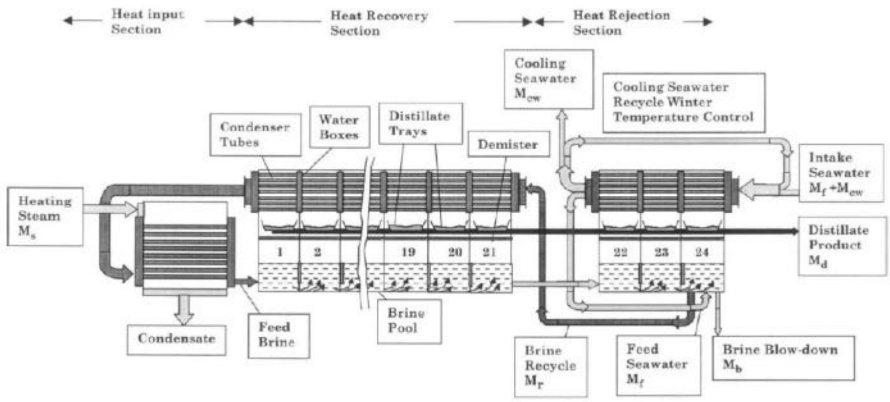
MSF Process



Source: El-Dessouky & Ettouney. Fundamentals of Salt Water Desalination (2002)

Multistage flash desalination with brine circulation

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MSF Process

- Another important feature is the **geometry of condensing tubes** in the chambers.
- Two main configurations can be found in industrial units:
  1. the ***Long Tube Configuration***, where the tube bundle crosses longitudinally a certain number of stages (6 to 8);
  2. the ***Cross Tube Configuration***, where the tube bundle crosses transversally each stage, requiring an external “water box” which connects the tube bundles of two subsequent stages.

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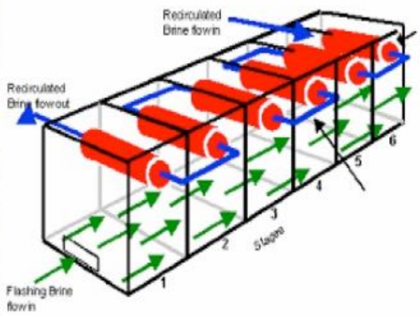
MSF Process

Cross Tube



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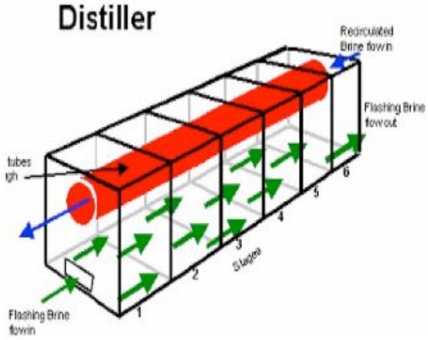
MSF Process

Long Tube Distiller



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MSF Process

- The main advantages and disadvantages of **Long Tube configuration** are:

  1. **pressure losses** along the tubes are **reduced by 25-30%** compared to the cross tube configuration;
  2. **no further elements (water boxes)** are needed to connect tube bundles between stages;
  3. **the fouling or breakage** of some of the tubes **may reduce significantly the efficiency** of the unit, affecting the condensation in a large number of stages;
  4. **maintenance and substitution** of tubes can be **very complex and expensive**.

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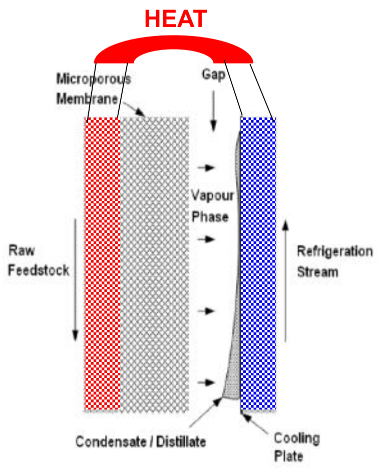
Membrane Distillation (MD)

Membrane Distillation (MD)

Membrane Distillation is an evaporative process in which water vapor, driven by a difference in vapor pressure, permeates through a hydrophobic membrane, thus separating from the salt water phase.

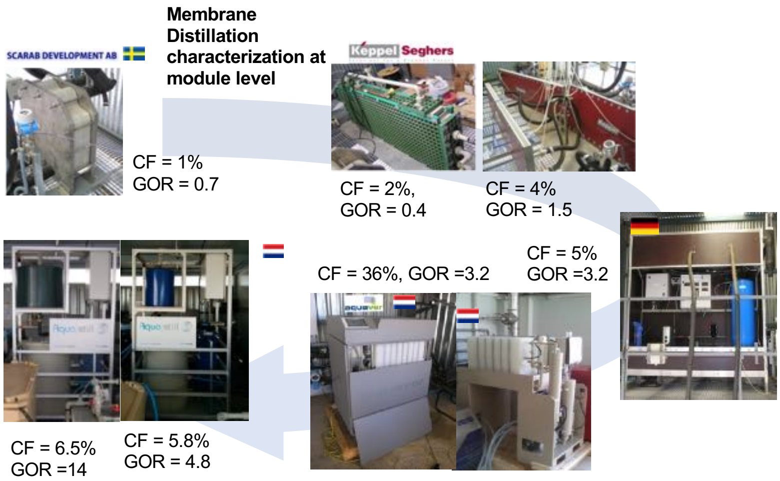
Once the vapor has passed through the membrane, it can be extracted or directly condensed in the channel on the other side of the membrane.



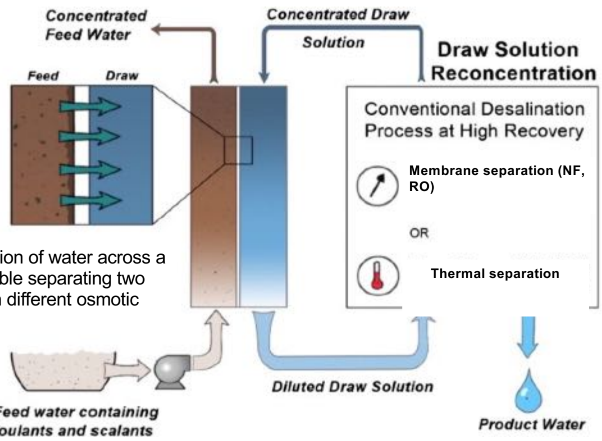
Advantages:

- The operating temperature is in the range of 60 to 80 °C.
- The membranes used in MD are **tested against fouling** **scaling**.
- **Chemical** feed water **pre-treatment is not necessary**.
- **Intermittent operation** of the module is **possible**.
- **100% theoretical salt rejection**; system efficiency quality are independent of salinity of the feed water.
- Less space and equipment requirements compared to th of thermal processes that result in capital savings.

Membrane distillation (MD)



Forward Osmosis (FO)



Natural diffusion of water across a semi-permeable separating two solutions with different osmotic pressures

Product water must be separated from the draw solution

Shaffer et al., Desalination 356 (2015), 271-284

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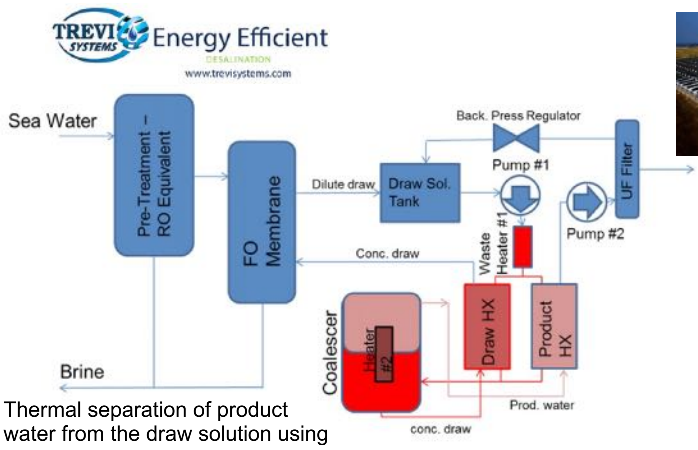
Forward Osmosis (FO)



NELHA Project

- 500 m^3/day
- High recovery (up to 60%)
- CSP + TES using volcanic rock and/or water

~30 kWh_{th}/m^3

~1 kWh_e/m^3

Thermal separation of product water from the draw solution using a coalescer

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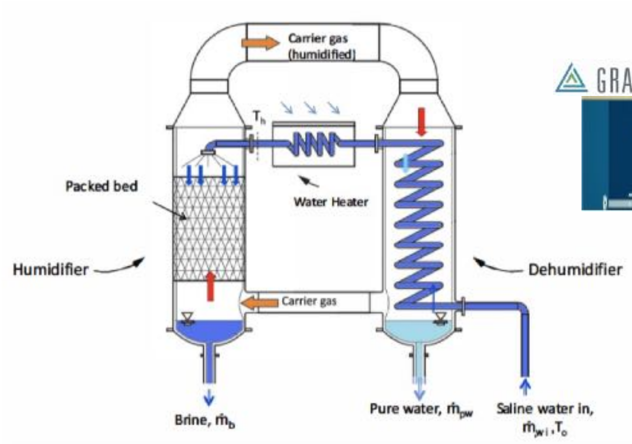
Humification – Dehumidification (H-DH)



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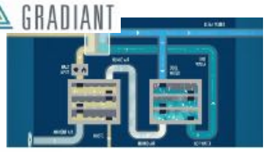

terra solar

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End of Presentation

- Thank you for your attention
- Questions?

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