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SOLMED: solar energy and polymers for seawater desalination

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ABSTRACT

Combining thermal solar energy and polymer materials allows seawater desalination while fossil fuels are saved and use of chemicals against fouling and corrosion is reduced. SOLar Multi-Effect Desalination (SOLMED) meets recommendations of the US National Research Council and Middle East Desalination Research Center of Oman regarding the future of water desalination. Water cost reduction and development of technologies with low environmental impact are the main guidelines of SOLMED. Thermal efficiency is at the heart of SOLMED. Process is based on low-temperature multi-effect distillation (LT-MED) powered by a thermal solar collector field, or better, by heat recovery at the outlet of a solar power plant. Heat transfer surfaces are made of thin wall polymer tubes to ensure a high thermal duty in spite of low thermal conductivity of polymers. Targeted capacities lie within 500–1,000 m^3/d. The objective is to develop a LT-MED prototype made of polymers and to operate the system plugged to a solar heat source. To reach these objectives, SOLMED gathers a consortium of six partners, merging experts of thermal systems and components, experts in polymers and transformation, and engineering partners in the field of solar energy and processes. Social aspects are also taken into account through acceptability, sustainability, design, management of innovation, market, and life cycle assessment. SOLMED is a three years project funded by the French National Research Agency. The first step is to build a 10 m^3/d prototype to bring a proof of concept. The prototype will be operated with a 100 kW peak solar heat source. Developments are related to the modeling of the process itself and its integration in a solar system including heat storage, thin-wall tubes fabrication, optimization of tubes fixing, investigations related to heat transfer, and hydraulic.

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Regarding polymer materials, the challenge is to combine high thermal rate with long lifetime. Commercial step has to consider new optimization approach, taking into consideration the whole process, including heat source.

Keywords: Desalination; Distillation; Multi-effect; Low temperature; Polymer; Solar energy; Life cycle assessment

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1. Introduction

The use of polymer surfaces to transfer heat between two fluids is not new. First development by DuPont appeared in 1965 for tubes and shell heat exchangers made of Teflon® [1]. Due to poor thermal conductivity of polymers, at least 100 times less than common metals, only specific applications can benefit of polymers: when thermal performances are not the main goal or when thermal duty is not affected by wall thermal resistance. Most common examples are:

- Heating or cooling of highly corrosive fluids: thermal performances are not priority compared with resistance to corrosion; heat transfer regime is natural convection in the case of immersed coils.
- Air/air heat transfer: air side heat transfer coefficient is low, even in the case of moist condensation, making that wall thermal resistance contribution to overall resistance is rather low [2].

Fig. 1 shows the effect of wall thermal resistance on overall heat transfer coefficient for different regimes of heat transfer. Considering a CuNi 90/10 wall with a thickness of 1 mm as a reference, any polymer, material and thickness, can replace metal in many air/air and laminar liquid/liquid heat exchangers. In evapo-condensers, widely used in thermal desalination processes, using a thick polymer decreases dramatically thermal performances. But using thin-wall tubes leads to thermal performances only within 20–30% below metal ones if a relatively conductive polymer is used, such as HDPE. But considering that polymers surface is hydrophobic with a good durability on condensation side, dropwise condensation regime shrinks the gap between metal and polymer performances. It has been observed that HDPE thin tubes can transfer heat as well as CuNi tubes [3].

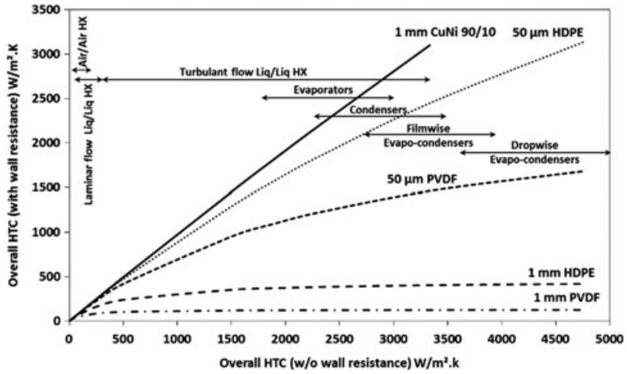


Fig. 1. Effect of wall resistance on overall heat transfer for different thermal processes.

Cost of raw polymer materials are rather low compared with metal ones and low density of polymers increases the cost ratio in favor of polymers. But unfortunately, manufacturing of large heat transfer polymer surfaces remains costly. For this reason, application of polymers to desalination is presently limited to small capacity units generally based on cycle of humidification and dehumidification of air. Resistance to corrosion is ensured while thermal resistance of wall is not critical due to air side poor transfer [2,4].

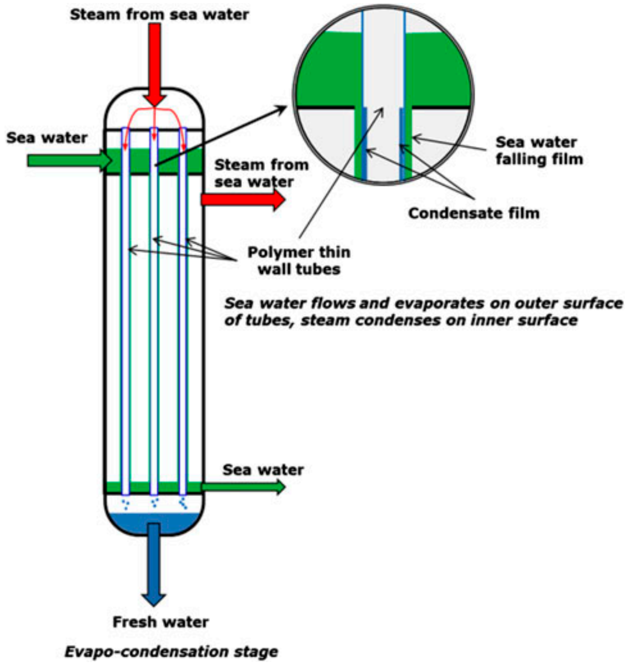


Fig. 2. One effect of evapo-condensation.

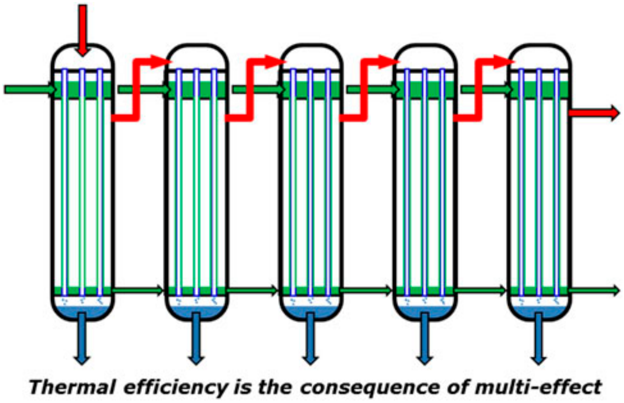


Fig. 3. Multi-effect arrangement.

SOLar Multi-Effect Desalination (SOLMED) project has an objective to update this approach using thin-wall tubes combined with a falling film multi-effect process. Use of a low-temperature heat source combined with expected good thermal performances makes that the difference of temperature between effects and the resulting pressure difference is minimum. This leads to low mechanical stress on the material ensuring a long lifetime.

Figs. 2 and 3 show fluids circulation in a single effect adopted in SOLMED and arrangement of Vertical Tubes Evaporators to obtain multi-effect evaporation.

2. SOLMED overview

Three main principles characterize SOLMED:

- Multi-effect distillation on vertical tubes brings thermal efficiency to the process itself and flexibility to operating conditions. Production can vary easily within ±20–30% of nominal capacity; this is an advantage when heat source is not constant in time as a solar heat source.
- The use of thin-wall tubes (50–100 μm) made of polymers as heat transfer surface brings low cost due to the material itself and the low amount to be used. Excellent behavior of polymers used in corrosive and fouling conditions reduces or even cancel the use of most of chemicals generally used in desalination plants, leading to an impressive environmental gain.
- Heat source is solar, directly coupled to desalination unit, or better, downstream to a CSP power plant. In this last case, marginal cost of energy is very low, as in any case of dual purpose plant. For both cases, carbon footprint is very low. SOLMED can use any waste heat, solar or not, to benefit of low cost and low carbon footprint energy.

Considering above characteristics, SOLMED meets recommendations of US National Research Council in Review of the Desalination and Water Purification Technology Roadmap and Desalination: A National Perspective [5,6]. SOLMED complies also with Middle East Desalination research Center research program and policy [7]. SOLMED ambition is to be cost effective regarding capital and operation costs, and to have a low environmental impact regarding energy source and chemicals to be used and released into brine.

3. Scientific and technical challenges

Fabrication of polymer thin films is commonly done for packaging. Manufacturing process is extrusion blowing: bubble diameter is given by internal pressure and die sizing while required thickness is reached by adjustment of pulling speed. If thickness control is critical for packaging, as it drives the final product quality and cost, diameter can varies slightly without drawback. Defectivity is also allowed if it remains within an acceptable range.

Applied to heat transfer, thin-wall tubes can also be fabricated by extrusion blowing process. But tolerances on specifications are much narrower because thickness controls heat transfer, diameter, the ability to be mounted on tubes sheet, and fitting with liquid distributors at inlet and separator at outlet. Zero defect is required, otherwise lifetime drops dramatically. Thermal conductivity of final product is also a critical parameter: thin film extrusion orientates polymer chains, making changes of physical, thermal, and mechanical properties, compared with massive raw material.

Tubes' fitting with tube sheet is to be done mechanically, by use of additional devices. Upper fixation ensures three functions: tube fixation, seawater distribution, and inlet of heating steam. Bottom fixation insures four functions: tube fixation, free expansion, separation of seawater and condensate, and non-condensable gas venting.

Even if surfaces of polymers are less sensitive to fouling than metal ones, a good behavior to biofouling and scaling is to be demonstrated. As surfaces are flexible, it is expected that fouling layer will be periodically broken leading to an auto-cleaning effect.

Management of non-condensable gas is a well-known issue in large power condensers. Accumulation of air due to leaks into units working below atmospheric pressure and seawater make-up outgassing can block condensation leading to shutdown of desalination unit. As condensation occurs inside the tubes, each tube is naturally and individually swept by steam velocity. A calibrated leak at the tube end between condensation and evaporation sides makes that a small amount of steam and air flows from one effect to another one to reach finally the final condenser. An absolute control of non-condensable gas path along the evaporation line is necessary to insure a safe operation of SOLMED. This analysis is strongly linked to the determination of thermal performances of the evapo-condensers and knowledge of heat transfer coefficients on evaporation and condensation side.

As coupling with a solar source brings heat to desalination unit with a profile of thermal power and with long periods of shut down when solar energy is not available, a strategy of operation has to be defined. This includes sizing of unit, sizing of solar collectors field, sizing of eventual heat storage if this option is adopted, and determination of production profile to maximize global efficiency of conversion from solar radiation to water production.

Finally, cost evaluation of a reference unit of 1,000 m^3/d and its operation cost will allow determining a water cost according to financial hypothesis. Considering advantages of SOLMED, this cost must be attractive.

4. Market and target cost for SOLMED

Even if there is no objective reason preventing from extending SOLMED capacity to large plants, targeted capacity lies within 500–1,000 m^3/d. This is more or less the capacity of half the built units during the past decade, considering all processes together (analysis based on DesalData plant inventory [8]). Fig. 4 summarizes data from different sources; it shows that market-specific cost of MED desalination plant in this range of capacity is 4,000–3,000 US $\$/(m^3/d)$ [9–13]. Final water cost depends strongly on energy cost. Evaluation shows that 1 US$/$m^3$ may be reached by SOLMED in this capacity range if marginal cost of thermal energy is null.

5. Modeling tasks

A full techno-economic model of desalination plant built with polymer vertical tubes has been established. Without entering in detailed description, it takes into account process data describing available heat source, pressure drops, technical options, and cost functions including financial model. For a targeted capacity or for an available thermal power, model determines optimized unit chosen in a set of 14 calculated units, comprising 1–14 effects. Optimization is based on minimum levelized water cost calculated over the lifetime of the unit. Fig. 5 shows an extraction of process data sheet (a) and summarized results (b). In this example, minimum water cost is obtained with 10 effects; specific capital cost is near 2,200 $\$/(m^3/d)$. Details about unit construction and costs breakdown are also calculated. Material balance and energy consumption during plant lifetime are calculated to determine carbon footprint of water production.

A reverse calculation module able to determine water production of a given unit when inlet conditions (temperature and flow rates) vary is also available. This module is also coupled with a model of solar heat source including heat storage, heat recovery from any source, and air cooled heat exchanger.

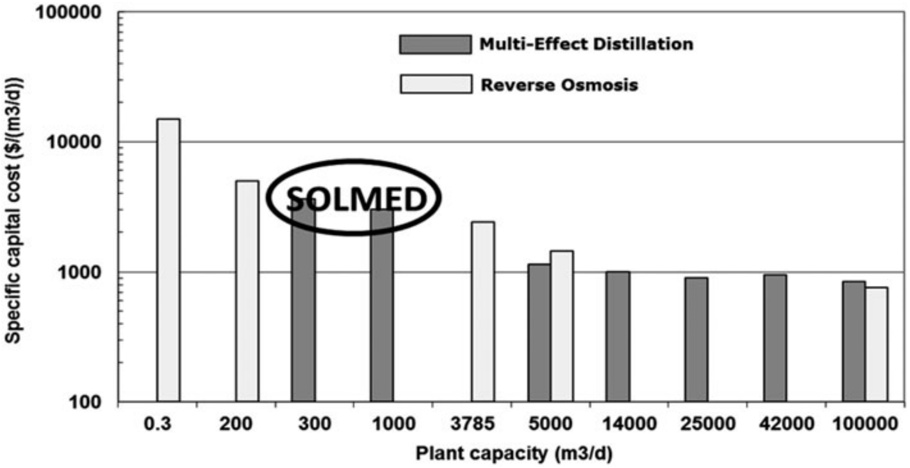
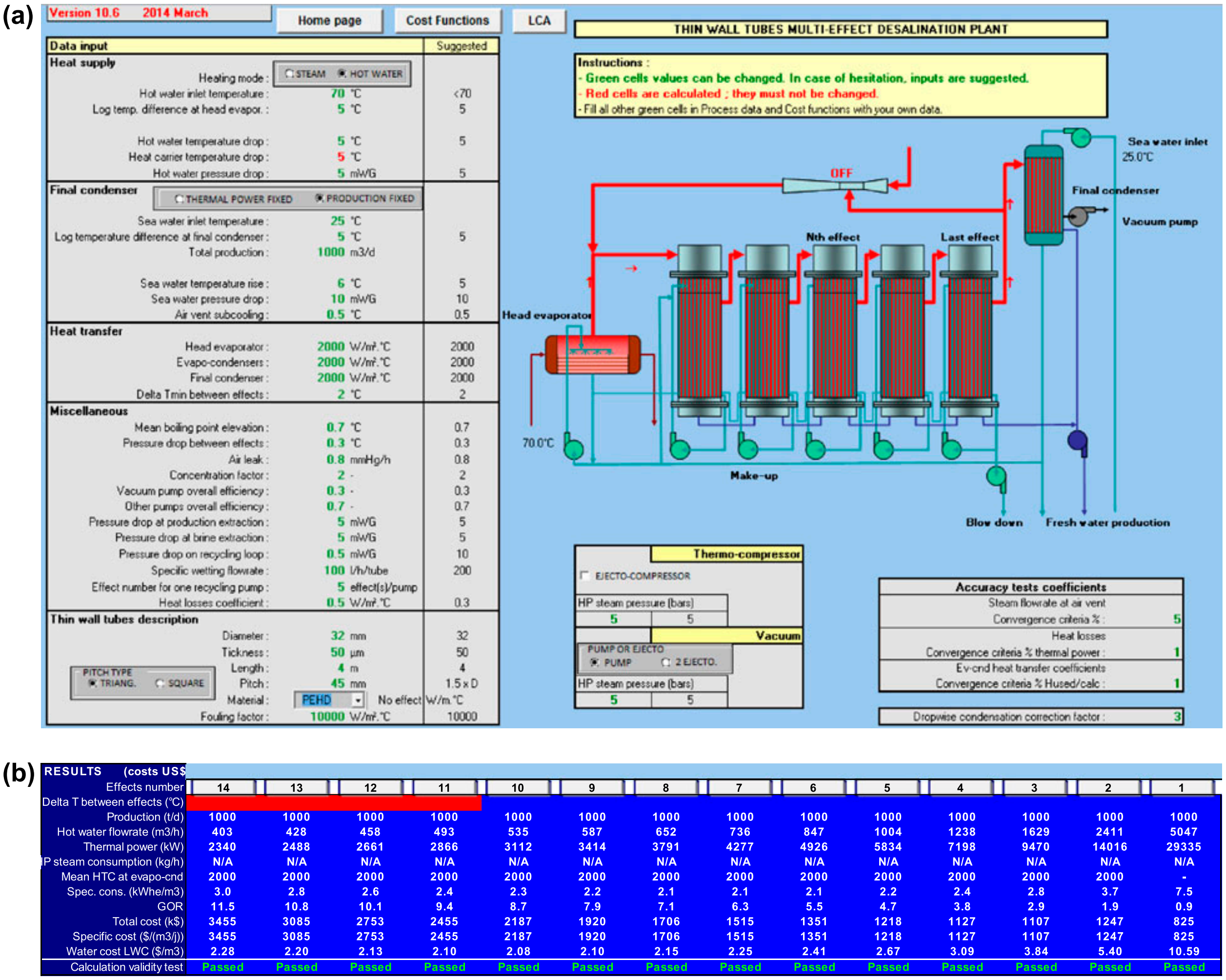


Fig. 4. Market cost of MED and RO desalination plants in function of capacity.



THIN WALL TUBES MULTI-EFFECT DESALINATION PLANT

Instructions :
- Green cells values can be changed. In case of hesitation, inputs are suggested.
- Red cells are calculated ; they must not be changed.
- Fill all other green cells in Process data and Cost functions with your own data.

Data input			Suggested
Heat supply			
Heating mode :	○ STEAM ● HOT WATER		
Hot water inlet temperature :	70	°C	<70
Log temp. difference at head evapor. :	5	°C	5
Hot water temperature drop :	5	°C	5
Heat carrier temperature drop :	5	°C	
Hot water pressure drop :	5	mWG	5
Final condenser	○ THERMAL POWER FIXED ● PRODUCTION FIXED		
Sea water inlet temperature :	25	°C	
Log temperature difference at final condenser :	5	°C	5
Total production :	1000	m3/d	
Sea water temperature rise :	6	°C	5
Sea water pressure drop :	10	mWG	10
Air vent subcooling :	0.5	°C	0.5
Heat transfer			
Head evaporator :	2000	W/m².°C	2000
Evapo-condensers :	2000	W/m².°C	2000
Final condenser :	2000	W/m².°C	2000
Delta Tmin between effects :	2	°C	2
Miscellaneous			
Mean boiling point elevation :	0.7	°C	0.7
Pressure drop between effects :	0.3	°C	0.3
Air leak :	0.8	mmHg/h	0.8
Concentration factor :	2	-	2
Vacuum pump overall efficiency :	0.3	-	0.3
Other pumps overall efficiency :	0.7	-	0.7
Pressure drop at production extraction :	5	mWG	5
Pressure drop at brine extraction :	5	mWG	5
Pressure drop on recycling loop :	0.5	mWG	10
Specific wetting flowrate :	100	l/h/tube	200
Effect number for one recycling pump :	5	effect(s)/pump	
Heat losses coefficient :	0.5	W/m².°C	0.3
Thin wall tubes description			
Diameter :	32	mm	32
Tickness :	50	µm	50
Length :	4	m	4
Pitch :	45	mm	1.5 x D
Material :	PEHD	No effect	W/m.°C
Fouling factor :	10000	W/m².°C	10000

PITCH TYPE ● TRIANG. ○ SQUARE

Thermo-compressor

☐ EJECTO-COMPRESSOR

HP steam pressure (bars)	
5	5

Vacuum

PUMP OR EJECTO ● PUMP ○ 2 EJECTO.

HP steam pressure (bars)	
5	5

Accuracy tests coefficients	
Steam flowrate at air vent Convergence criteria % :	5
Heat losses Convergence criteria % thermal power :	1
Ev-cnd heat transfer coefficients Convergence criteria % Hused/calc :	1

Dropwise condensation correction factor : 3

RESULTS (costs US$														
Effects number	14	13	12	11	10	9	8	7	6	5	4	3	2	1
Delta T between effects (°C)														
Production (t/d)	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000
Hot water flowrate (m3/h)	403	428	458	493	535	587	652	736	847	1004	1238	1629	2411	5047
Thermal power (kW)	2340	2488	2661	2866	3112	3414	3791	4277	4926	5834	7198	9470	14016	29335
P steam consumption (kg/h)	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Mean HTC at evapo-cnd	2000	2000	2000	2000	2000	2000	2000	2000	2000	2000	2000	2000	2000	-
Spec. cons. (kWhe/m3)	3.0	2.8	2.6	2.4	2.3	2.2	2.1	2.1	2.1	2.2	2.4	2.8	3.7	7.5
GOR	11.5	10.8	10.1	9.4	8.7	7.9	7.1	6.3	5.5	4.7	3.8	2.9	1.9	0.9
Total cost (k$)	3455	3085	2753	2455	2187	1920	1706	1515	1351	1218	1127	1107	1247	825
Specific cost ($/(m3/j))	3455	3085	2753	2455	2187	1920	1706	1515	1351	1218	1127	1107	1247	825
Water cost LWC ($/m3)	2.28	2.20	2.13	2.10	2.08	2.10	2.15	2.25	2.41	2.67	3.09	3.84	5.40	10.59
Calculation validity test	Passed	Passed	Passed	Passed	Passed	Passed	Passed	Passed	Passed	Passed	Passed	Passed	Passed	Passed

Fig. 5. (a) Process data of thin-wall tubes desalination unit. (b) Summarized results and optimum water cost determination.

6. Prototyping

A five-effect prototype has been designed. For finalization, it will be coupled to electric hot water generator, in controlled conditions to simulate steady state regime and daily sunny hours. Then, prototype will be moved to CEA Cadarache solar platform to be coupled with solar heat source. Prototype main characteristics are given in Table 1.

Prototyping steps are tubes fabrication and their characterization, engineering of utilities, design and fabrication of modules, and their integration. In parallel, a single tube evapo-condenser is built in order to measure heat transfer coefficient in different conditions: temperature, falling film flow rate, and air concentration.

6.1. Tubes fabrication and characterization

As previously mentioned, tubes are made by thin extrusion blowing of a polyolefin. Fig. 6 shows a tube during extrusion and a roll of finished flexible tube. Different thicknesses have been fabricated in order to measure thermal conductivity by hot disc method. Table 2 summarizes first-generation tubes characteristics and specifications.

Material properties are not sufficient to insure durability of desalination equipment. To this effect, an artificial ageing test rig has been built (Fig. 7). Temperature is increased up to 80°C to accelerate ageing without threshold effect in material and strength three times higher than maximum nominal one is applied. Strength results of internal air pressure

Table 1
SOLMED prototype main characteristics

	Full capacity	Half load
Effect number	4 + 1	4 + 1
Head temperature	70°C	50°C
Hot water flow rate	5.4 m^3/h	5.4 m^3/h
Seawater temperature	25°C	25°C
Seawater flow rate	7.8 m^3/h	7.8 m^3/h
ΔT head evaporator	8.9°C	4.5°C
ΔT between effects	3.4°C	1.7°C
ΔT final condenser	8.9°C	4.5°C
Evaporator thermal power	56 kW	28 kW
Condenser thermal power	50 kW	25 kW
Head evaporator surface	3.2 m^2	3.2 m^2
Evapo-condensers surface	7.7 m^2	7.7 m^2
Final condenser surface	2.8 m^2	2.8 m^2
Number of tube/effect (L = 4 m v32 mm pitch 45 mm)	19	19
Recycling flow rate (200 l/h/tube)	15.2 m^3/h	15.2 m^3/h
Fresh water production	375 l/h (9.0 m^3/j)	186 l/h (4.5 m^3/j)
Make-up flow rate	750 l/h	370 l/h
Brine flow rate	375 l/h	190 l/h
Air vent flow rate	4 m^3/h	4 m^3/h
Air vent pressure	44.2 mm Hg	44.2 mm Hg

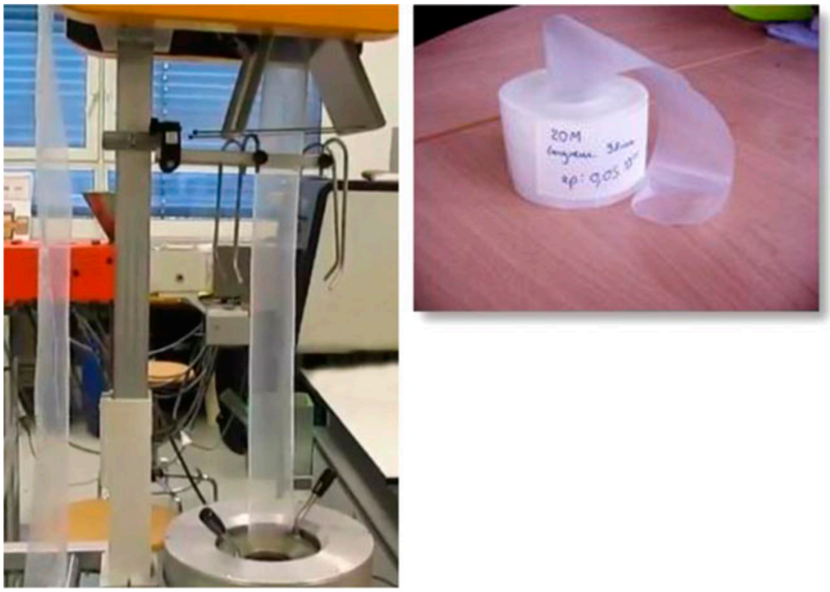


Fig. 6. Thin wall tube fabrication.

applied, the end of the tubes being plugged. This test rig allows determining lifetime of the tubes as a function of temperature and strength, instant expansion coefficient, and creeping and initial shrinkage at first temperature rise. As tubes temperature is controlled by a hot water falling film, the rig allows also checking wettability of surface and efficiency of liquid distributors at the top of the tubes. System is adiabatic, no heat transfer occurs between inside and outside of tubes. Ten tubes can be tested simultaneously.

Table 2
Tubes characteristics

Sample	Width (mm)	Thickness (μm)	Thermal conductivity (W/mK)	Strength (MPa)
Specification	50 ± 0.5	50 ± 5	0.4 ± 0.1	20
Material data	–	–	0.3–0.4 (40–93°C)	27
#1	49.5	50 + 0/10	0.26 (20°C)	24–34 axial, 20 tangential
#2	49	90 ± 5		
#3	49	50 + 0/10		
#4	49.5	80 + 0/10		

Fig. 7. Ageing test rig of polymer tubes.

6.2. Utilities and integration

At this state of advancement, utilities are under construction and prototype under quotation. As unit will not be operated at seaside at this state of project, artificial seawater is used from a 10 m^3 tank. Brine and production are mixed and recycled. To avoid temperature rise in the tank, a chiller keeps seawater temperature constant. Fig. 8 shows CAD arrangement of utilities, with reservation room to plug prototype.

Each utility skid as a specific function:

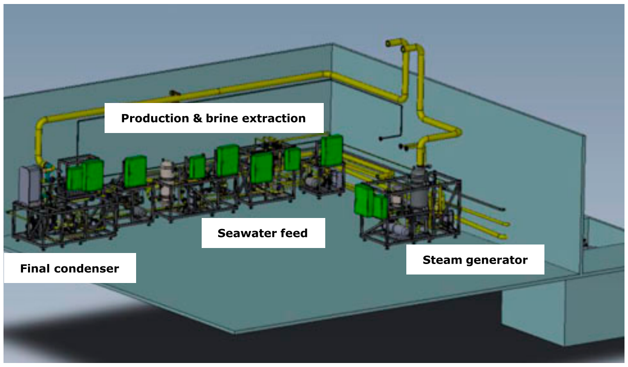


Fig. 8. Utilities to operate SOLMED.

- steam generation from hot water to feed first effect,
- final condenser with air vent,
- make-up to MED,
- fresh water extraction,
- brine extraction,
- seawater conditioning and
- seawater feed of final condenser.

Seawater tank and chiller are not visible in this view as they are outside of the building.

Fig. 9 gives a general aspect of prototype with scale. Global elevation of unit is 6 m from ground. Each effect diameter is 315 mm. Four evapo-condensers are used; with addition of final condenser stage, five effects of MED are available. Heating steam feeds the first effect on the left while produced steam of fourth effect flows to final condenser on the right.

6.3. Heat transfer characterization

Overall heat transfer through tubes’ wall is the result of evaporation and condensation rate on both sides and thermal resistance of wall. To reach each

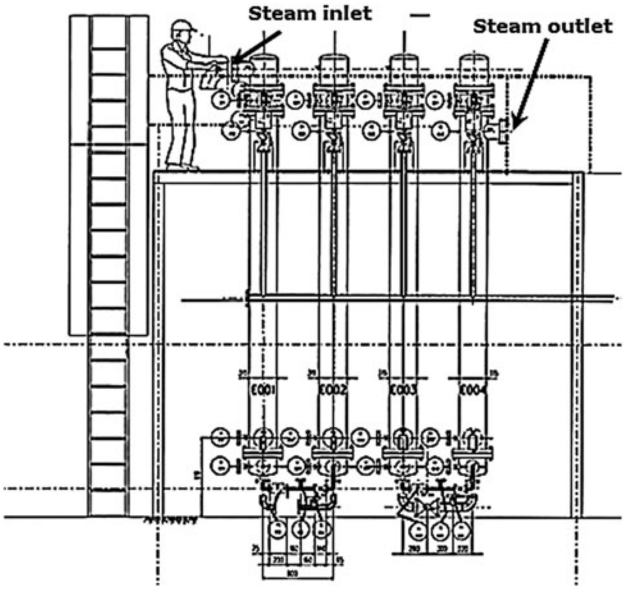


Fig. 9. General SOLMED prototype layout.

contribution, thermal conductivity is measured separately and modified Wilson plot method [14] is used for evaporation and condensation. For evaporation and condensation, we assume that heat transfer laws from literature can be used, with a simple adjustment factor, *Ce* and *Cc*. For evaporation side, Chun and Seban [15] correlation for a falling film on vertical surface gives:

$$he = Ce\left\{k\left(\frac{g}{v^2}\right)^{1/3}\left(\frac{4\Gamma}{\mu}\right)^{0.4}\left(\frac{\mu Cp}{k}\right)^{0.65}\right\} = Ce\ F \tag{1}$$

For condensation side, in the case of filmwise condensation, a law with Nusselt form for a vertical surface [16] can be used:

$$hc = Cc\frac{k}{L}\left\{\frac{L^3\rho(\rho-\rho_v)g[\Delta H + 0.68Cp\Delta T]}{\mu k\Delta T}\right\}^{1/4} = Cc\ G \tag{2}$$

For dropwise condensation, condensation heat transfer coefficient can be given by Bonner model [17]:

$$hc = Cc\left[\frac{k}{\left(\frac{\sigma}{\rho g}\right)^{1/4}\left[\frac{kTc}{\rho_v\Delta H^2}\left(\frac{\sin\theta}{1-\cos\theta}\right)\left(\frac{\gamma+1}{\gamma-1}\right)\left(\frac{Rc}{2\pi}\right)^{1/2}\right]^{1/4}\left(\frac{2\sigma Tc}{\rho\Delta H\Delta T}\right)^{1/4}}\right]\left(\frac{\sin\theta}{1-\cos\theta}\right) \tag{3}$$

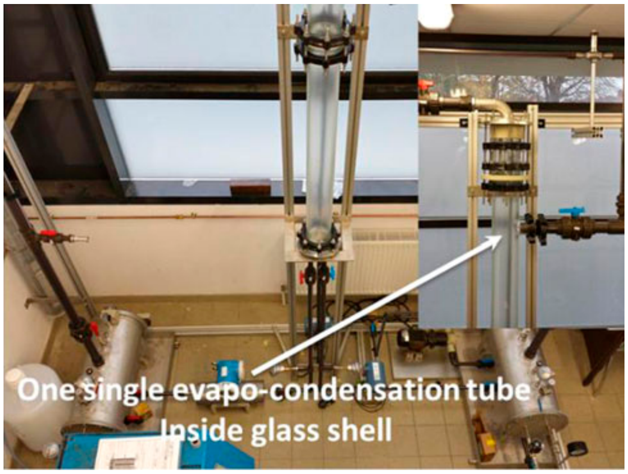


Fig. 10. Test rig to characterize heat transfer.

$$hc = Cc\ G \tag{4}$$

After data reduction, overall heat transfer coefficient is given by:

$$\left(\frac{1}{U}-\frac{e}{\lambda}\right)G = \frac{1}{Ce}\frac{G}{F}+\frac{1}{Cc} \tag{5}$$

Linearization allows to calculate *Ce* and *Cc* from measurements in different conditions.

$$Y = \frac{1}{Ce}X+\frac{1}{Cc} \tag{6}$$

Fig. 10 shows the test section comprising a single vertical tube inside a glass shell. Effective tube length is 2 m and its diameter is 32 mm.

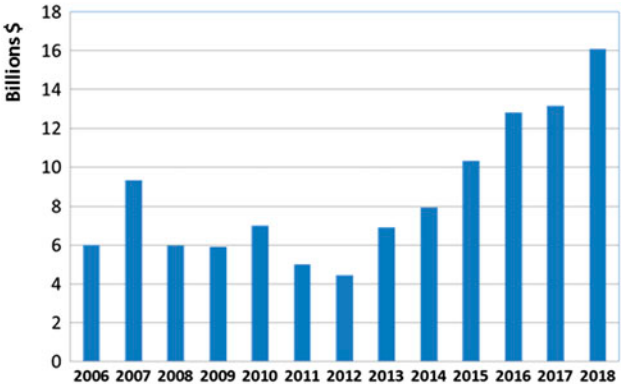


Fig. 11. Desalination annual market trend.

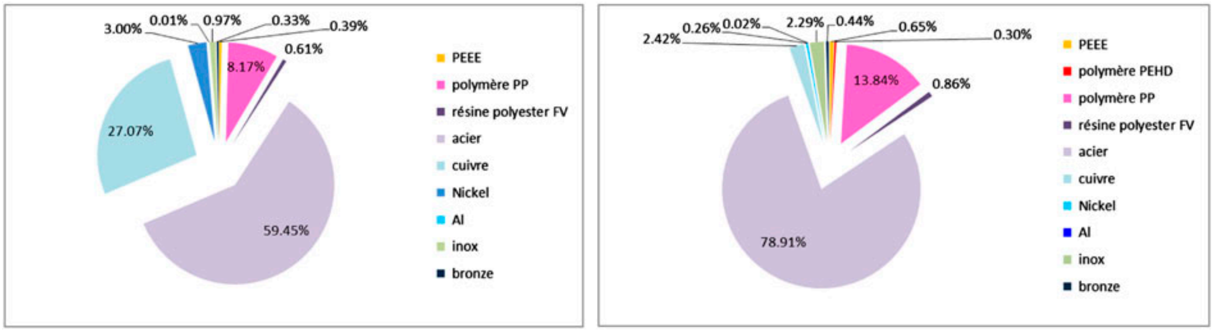


Fig. 12. Material balance for SOLMED (left) and for metallic evaporator (right).

7. Market study and carbon footprint resulting from life cycle assessment

Based on the analysis of 5,900 desalination units erected during the past decade or known to be planned in the short term, the average capacity is 450 m^3/d in the range below 1,000 m^3/d (data from reference [8]). This includes thermal and membrane processes. Considering a capital cost of about 3,000 $\$/(m^3/d)$ in this range of capacity, annual market is about 1 billion$ with an annual progression rate of about 10%. As SOLMED is designed, no technical showstopper prevents us to increase the capacity beyond 1,000 m^3/d in the future.

Analysis and projections on the period 2006–2018 (Fig. 11), show that after a relative stability of the market, a significant growth is forecasted in the next future [8]. Projections based on contracted plants are reliable.

If the market growth is located in well-known equipped countries (MENA countries, USA), a rapid growth in emerging countries is forecasted in the next five years. India and China will be the main contributors to this growth.

To evaluate the carbon footprint of SOLMED, data from Life Cycle Assessment at the present status of the project are used. Life cycle comprises following phases, with their impact of carbon footprint:

A comparison is established between a traditional metallic MED evaporator (horizontal tubes) and SOLMED plastic evaporator. Fig. 12 summarizes material balance.

Same hypothesis is adopted in both cases for transportation, without significant effect. During operation and maintenance, chemicals and energy (thermal and power) impact are estimated. Without any surprise, when plants are heated by fossil energy such as oil, the main contribution to carbon footprint is due to heating. Table 3 summarizes results.

As capital cost of SOLMED is slightly lower than a metallic evaporator one, optimization of water cost leads to 10 effects for SOLMED and eight effects for metallic evaporator. This explains differences of equivalent CO_2 counted for heating and power. SOLMED efficiency is 25% higher than metallic evaporator one.

Calculations with a solar heat source will make drop above figures as impact of heating will be strongly decreased, to reach zero if heat is considered as waste heat from a power cycle. For this last case, specific consumption of SOLMED utilities have to be optimized, especially brine recirculation power, to meet metallic evaporator ones.

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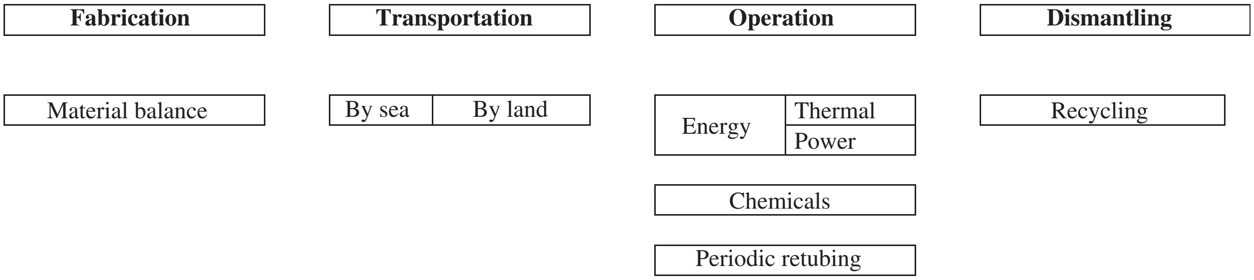

Table 3
Comparison of main CO_2 sources

	SOLMED plastic evaporator (kg/m^3)	Metallic evaporator (kg/m^3)
Equivalent CO_2 from heating	17.9	22.3
Equivalent CO_2 from power	1.9	1.5
Equivalent CO_2 from other sources	0.2	0.2
Total	20	24

Notations

Cc	constant to be determined in modified Wilson method for condensation side
Ce	constant to be determined in modified Wilson method for evaporation side
Cp	specific heat capacity, J/kg K
e	tube wall thickness, m
F	group of variables for modified Wilson method, evaporation side, $W/m^2 K$
G	group of variables for modified Wilson method, condensation side, $W/m^2 K$
g	gravitational acceleration, m/s^2
hc	heat transfer coefficient in condensation side, $W/m^2 K$
he	heat transfer coefficient in evaporation side, $W/m^2 K$
k	thermal conductivity, W/m K
L	length of tube, m
R	specific ideal-gas constant, $J/kg\ mol^{-1}$
Tc	condensation temperature, K
U	overall heat transfer coefficient, $W/m^2 K$
Γ	specific mass flow-rate, kg/s m
γ	ratio of isobaric to isochoric specific heat capacity
θ	contact angle, °
λ	thermal conductivity of tube, W/m K
μ	dynamic viscosity, Pas
ν	kinematic viscosity, m^2/s
ρ	density, kg/m^3
ρ_v	density of vapor, kg/m^3
σ	surface tension, kg/s^2
ΔH	latent heat of condensation, kJ/kg
ΔT	difference of temperature wall/vapor, K

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