تحت رعاية معالي رئيس مجلس الوزراء المصري المهندس شريف إسماعيل
مؤتمر تحلية المياه الحادي عشر في البلدان العربية
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Modelling and simulation of a hollow fiber module used for vacuum membrane distillation with solar energy

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Content

- Context
- Vacuum membrane distillation
- Desalination unit
- Modeling
- Results and discussion
- Conclusions

Context of the study

➢The crisis of drinking water announced for the coming years raise the interest of rapid development of desalination technologies:

- cheaper,
- simpler,
- more robust,
- more reliable
- less energy intensive
- environmentally friendly.

➢ In this context and as part of the European project MEDINA, we have designed and realized a membrane distillation unit coupled with solar energy.

➢In order to characterize the potential of this technique, we have modeled the functioning of the membrane module.

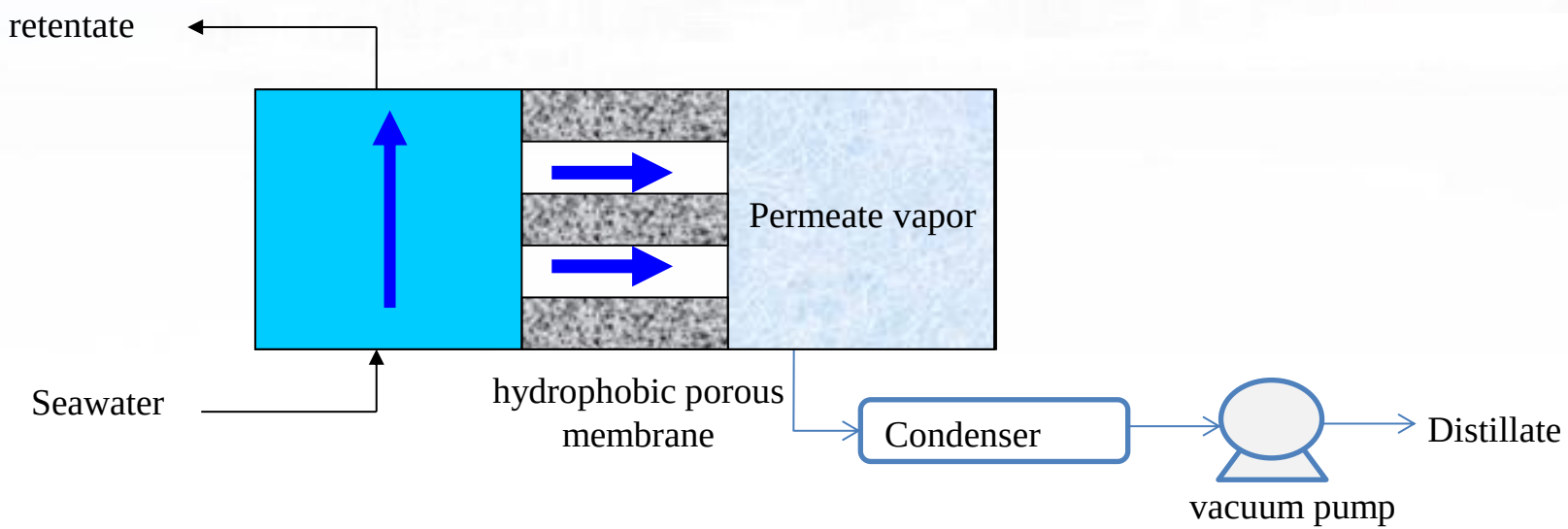
Vacuum membrane distillation

•Membrane distillation (MD) is a thermal membrane separation process which uses hydrophobic porous membranes

• The process driving force is the difference between the vapor pressure between the two sides of the membrane.

• Several membranes can be used (planes, hollow fibers, spiral module and tubular module)

• Desired temperature level: 70-80°C, Using solar energy to heat seawater.

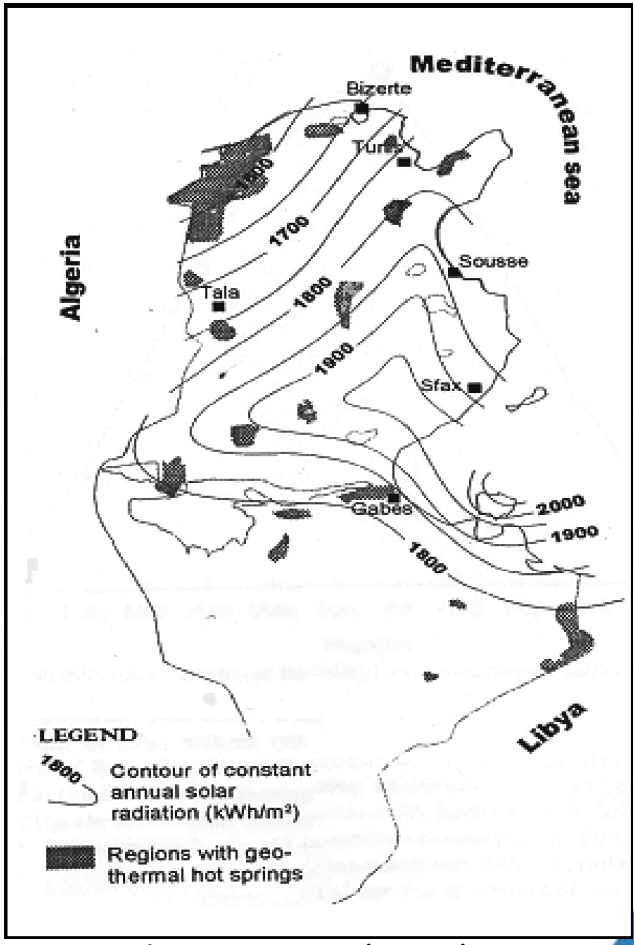


Solar energy in TUNISIA

Tunisia offers great opportunities for the development of solar applications through the exploitation of solar energy.

Its geographical location, Tunisia, as well as most of the other north Africans countries, enjoys an abundance of solar radiation:

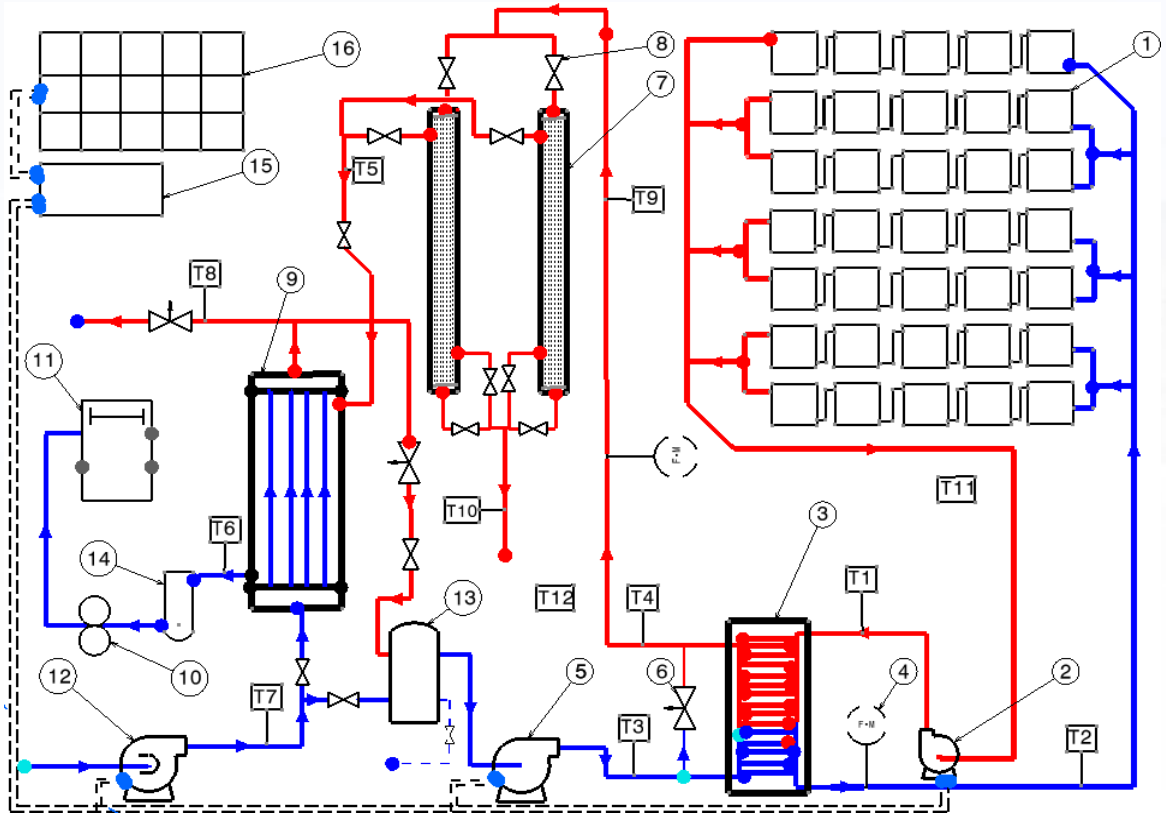
- The average of solar radiations exceeding 6 kWh/m^3/d for the months May, June, July, August and September.



Desalination 183 (2005)

Desalination unit

The choice of unit design is the result of work carried out in the project MEDINA.



1) Field of solar collector
2) Circulator
3) Plate heat exchanger
4) Flow meter
5) Flow pump
6) Electrovalve
7) Membrane module
8) Valve
9) Condenser
10) Peristaltic pump
11) Tank of fresh water
12) Flow pump
13) Mixing tank
14) Vase
15) Control module
16)Field of photovoltaic cell

Desalination unit

- The coolant fluid exiting the field of solar collectors is routed to the exchanger to heat the seawater.

- The seawater thus heated supplies the hollow fiber module.

- The amount of vapor produced supplies the condenser.

- The condensation of vapor preheats the flow of sea water supplementary.

Autonomous installation from an energy point of view :

- Field of solar thermal collectors ensuring the heating of water (70 m^2).
- Field of photovoltaic cells providing the electrical energy (16 m^2).

Hollow fiber module characteristics

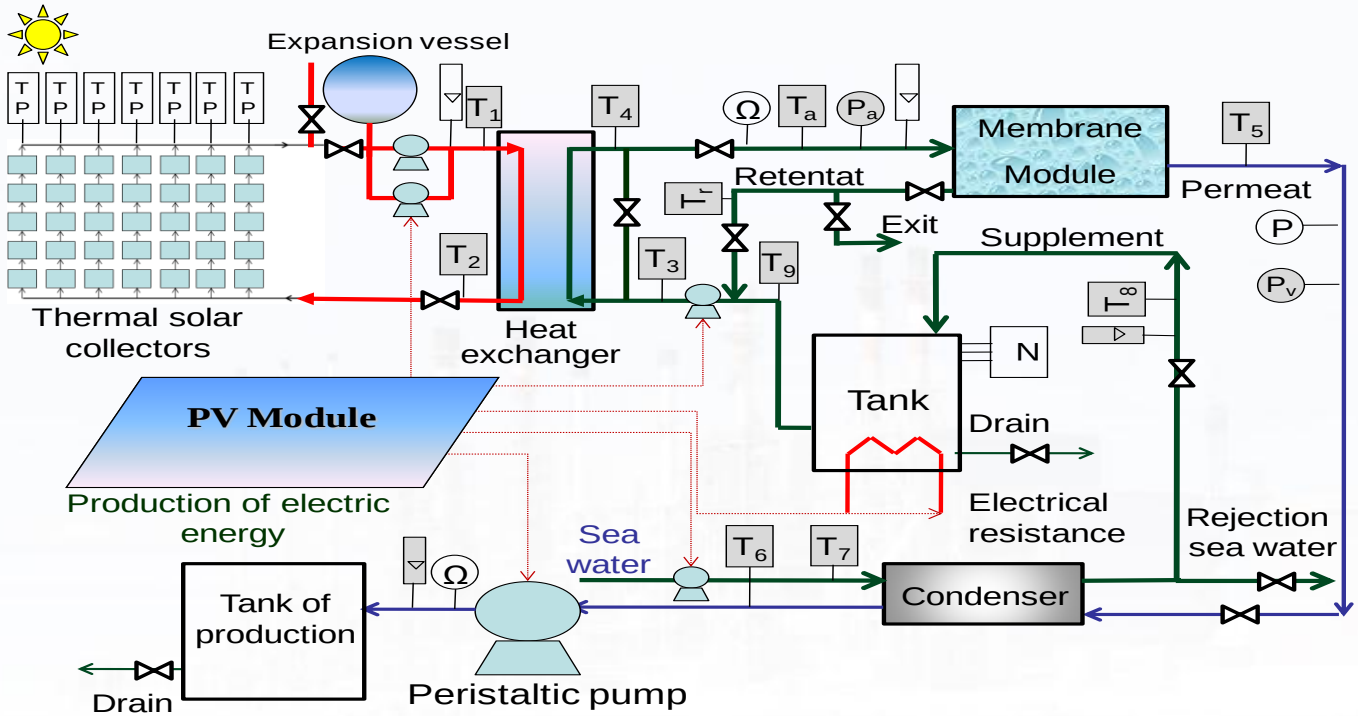
The hollow fiber module characteristics are selected so that it supports a high temperatures and have a good permeability

Choice of a hollow fiber module marketed by PALL Company.

Characteristics of the selected membrane module

Commercial reference	UMP 4247 R
Material	PVDF
Number of fibers	806
Thickness of the membrane (mm)	0.4
Module length (m)	1.129
Area (m^2)	4
Permeability at ($s.mol^{1/2} kg^{-1/2} m^{-1}$)	$1.92\ 10^{-6}$
Tortuosity	2.1

Dynamic modeling



Establishment of a knowledge model describing the functioning of the installation.

Model based on universal laws of physics, chemistry and mass and heat balances.

Solar flow

Ambient temperature

Solar collector field

Plate heat exchanger

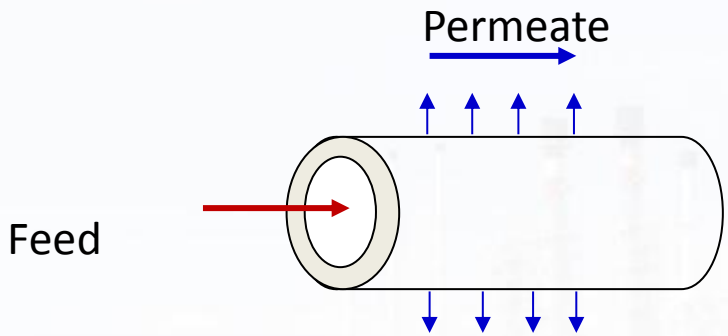
Condenser

Hollow fiber module

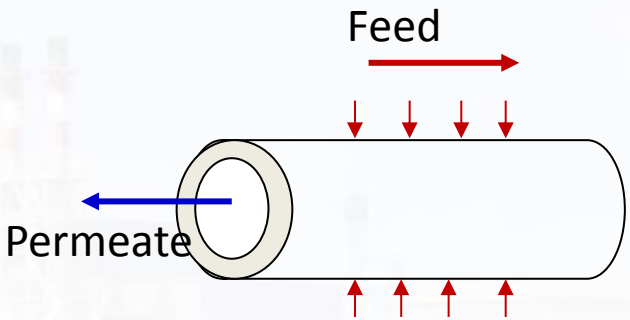
Dynamic modeling

Configurations

Internal - External



External - Internal



Objective: Elaboration of rigorous models describing the heat and mass transfer and allowing to the determination $T_{retentate}$, $T_{permeate}$, $Q_{retentate}$ and $Q_{permeate}$

Assumptions :

- The transfer of water vapor through the pores of the membrane is governed by Knudsen's diffusion mechanism.
- The flux density of water vapor through the interface membrane-water

$$J_v = K_m (P_i - P_{vacuum})$$

Dynamic modeling

Partial pressure Pi was written as a function of the activity coefficient.

$$P_i = \alpha_{water,NaCl}(1 - X_{NaCl})P_s$$

The saturated vapor pressure P_s can be expressed using the Antoine equation.

$$P_s = B_1 \exp\left(A_1 - \frac{A_2}{T_z - A_3}\right)$$

A_1 = 18,036 A_2= 3816,44 A_3 = 46,13 B_1 = 133,32

Heat and mass balances

$$\frac{dT_z}{dt} = -v_{feed}\frac{dT_z}{dz} - \frac{4J_v}{\rho_l\, d_{fib} Cp_l}\left[Cp_l\left(T_{ref} - T_z\right) + L_v\right]$$

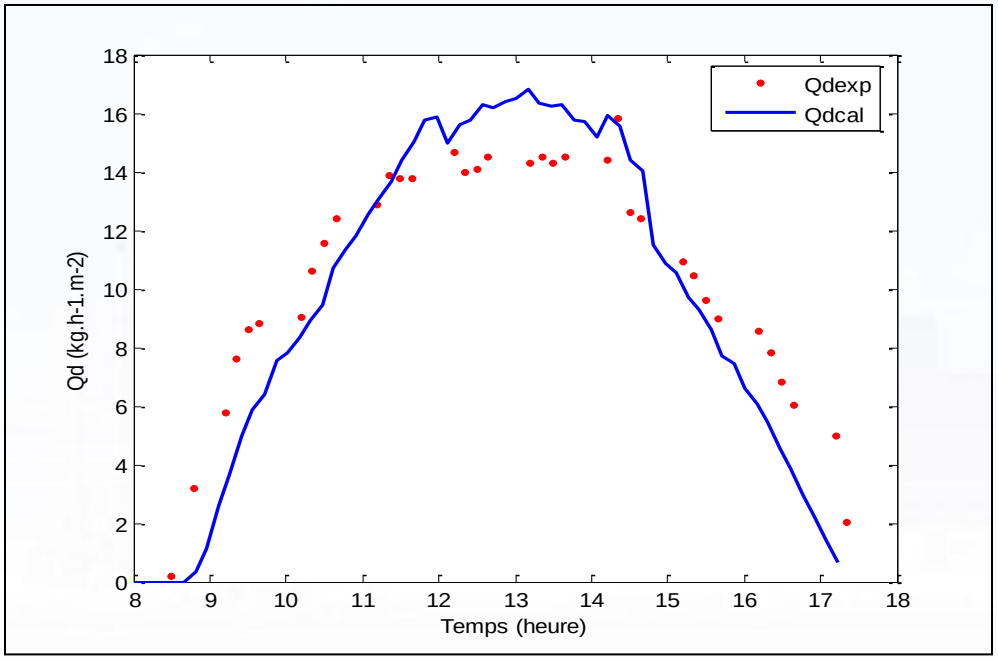
$$\frac{d\dot{m}_{dist}}{dz} = n_{fib}\pi d_{fib}\, J_v \quad \text{with} \quad J_v = K T_m^{-0,5}\left[\left(1 - 0.5X_{NaCl} - 10X_{NaCl}^2\right)\left(1 - X_{NaCl}\right)\exp\left(A_1 - \frac{A_2}{T_m - A_3}\right) - P_{vide}\right]$$

Systems of non-linear partial differential equations.

Development of resolution programs using MATLAB computing software.

Dynamic modeling

Experimental validation



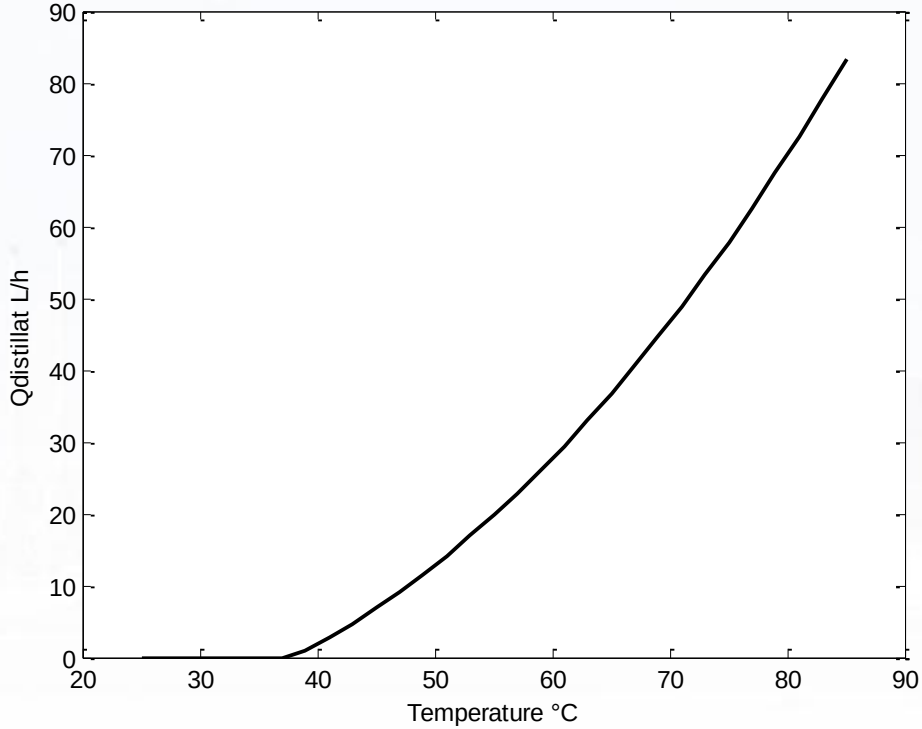
Comparison between the evolution of the distillate flow rate determined experimentally and calculated by the model.

Determination of uncertainty

Solar collector field	Exchanger	Hollow fiber module
8,2%	3,2%	15%

Simulation in steady state

Effect of temperature



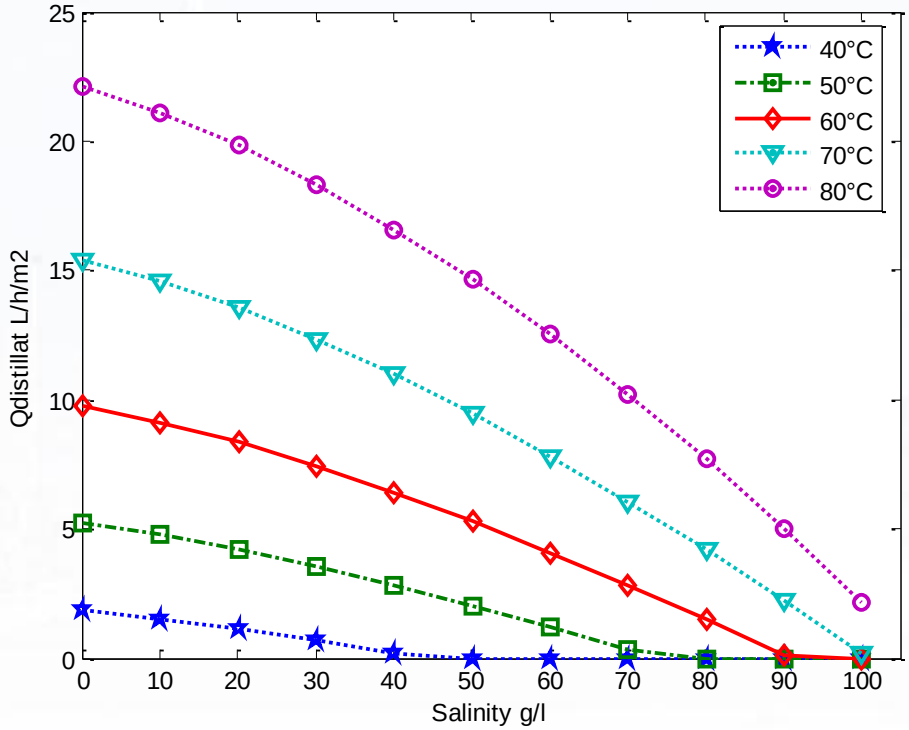
Influence of feed temperature, P_{vacuum} = 5000 Pa, $Q_{m,feed}$= 2233 kg/h, S_{NaCl}= 35 g/L

For a vacuum pressure of 5000 Pa, the evaporation temperature is around 37 °C.

Increasing the feed temperature allows to have a higher flow of distillate

Simulation in steady state

Effect of salinity

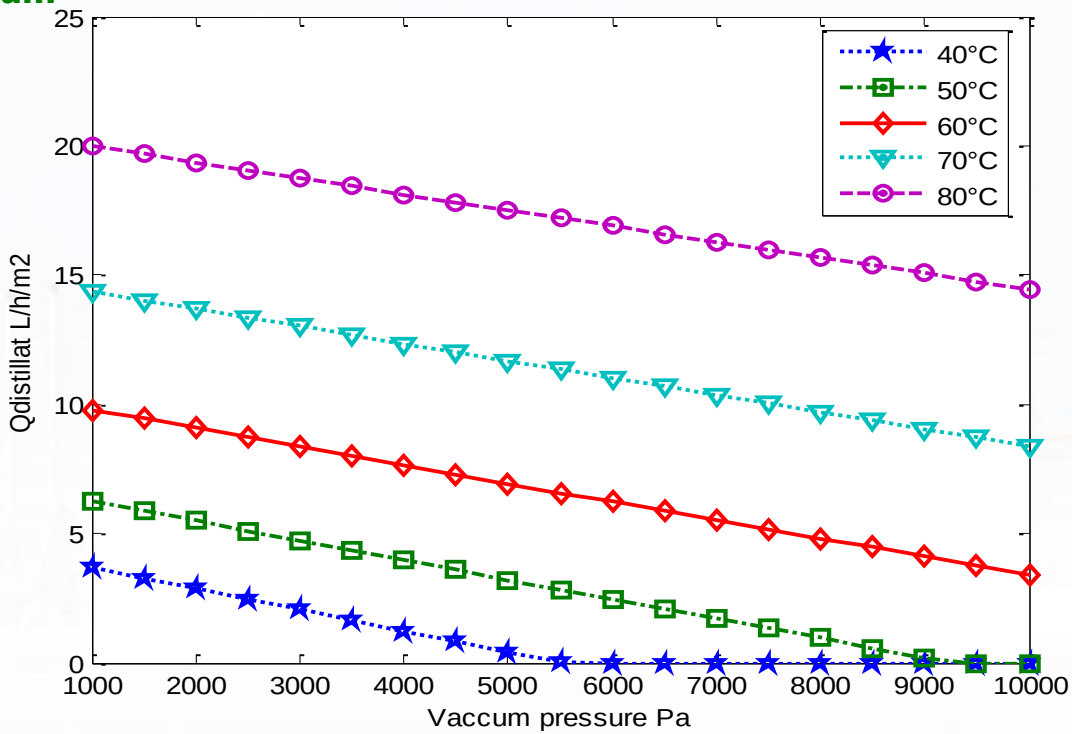


Influence of the salinity, P_{vacuum} = 5000 Pa, $Q_{m,feed}$= 2233 kg/h

Increase in salinity reduced remarkably the flow of distillate.
This is due to decreased activity of the seawater depending on the salinity.

Simulation in steady state

Effect of P_{vacuum}



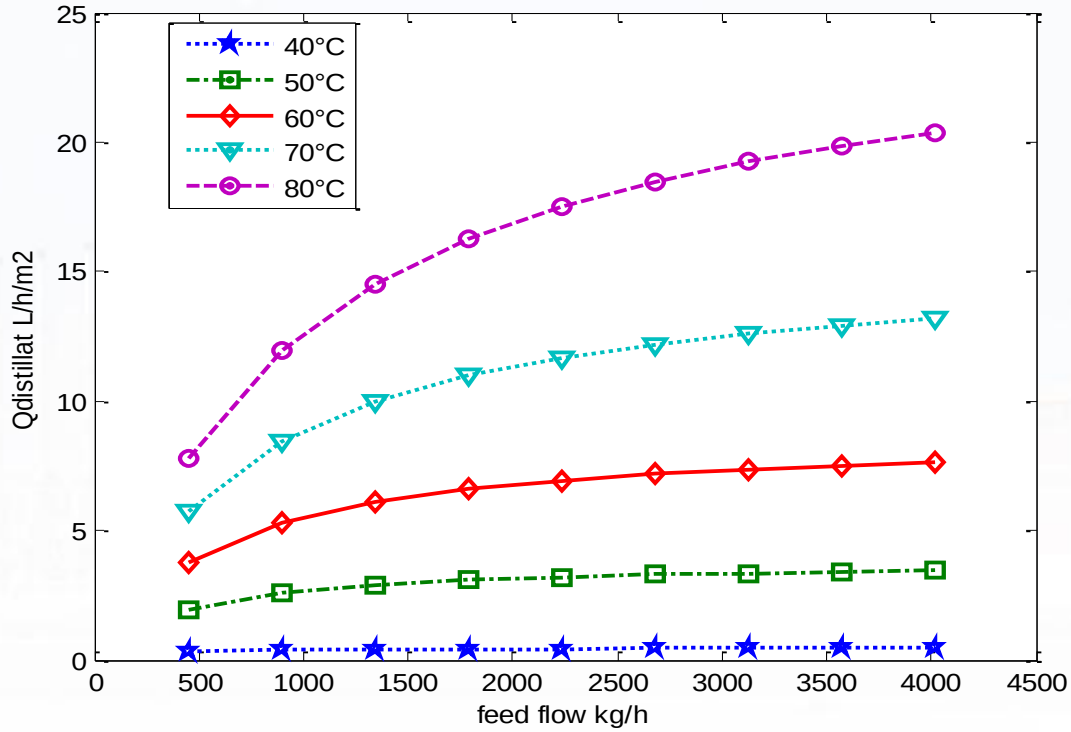
Influence of vacuum pressure, $Q_{m,feed}$= 2233 kg/h, S_{NaCl}= 35 g/L

The distillate flow rate gradually decreases with the reducing the vacuum level.

Work with reduced pressures allows the evaporation of seawater for relatively low T.

Simulation in steady state

Effect of $Q_{m,feed}$

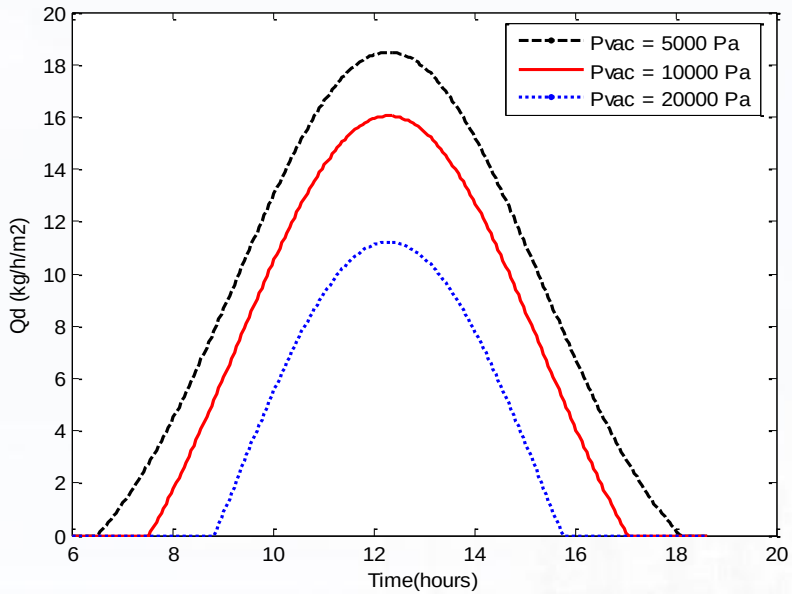


Influence of feed flow, P_{vacuum} = 5000 Pa , S_{NaCl}= 35 g/L

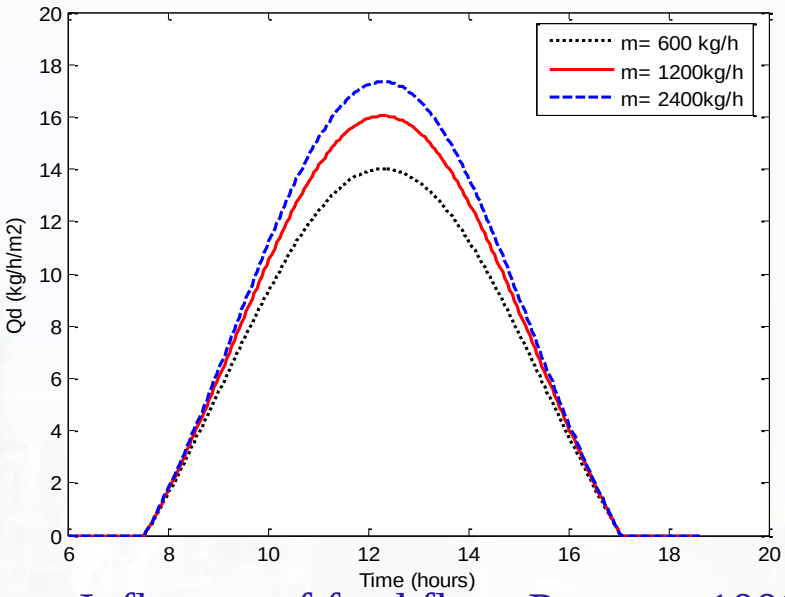
The flow rate of distillate increases with the feed flow rate.
This is due to the increase of the transfer coefficients (fluid velocity ↗ and turbulence ↗)

$\dot{m}_{feed}$

Simulation in dynamic state



Influence of vacuum pressure. $Q_{m,feed}$ = 1200 kg/h, $Q_{m,coolant}$= 770 kg/h,March 21



Influence of feed flow. P_{vacuum} = 10000 Pa , $Q_{m,coolant}$=770 kg/h, March 21

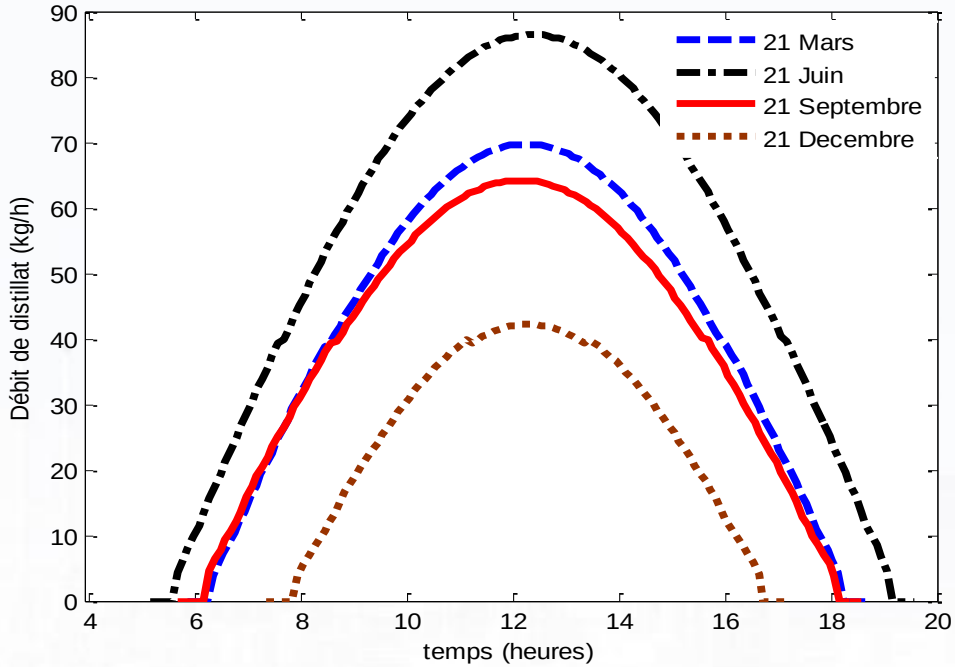
The distillate flow rate follows the solar flux.

The pressure gradient which is the driving force of the transfer.

Work with reduced pressures increase the duration of production.

The increase of distillate flow with the feed flow rate is due to the improvement of the transfer of heat and mass.

Daily production



$S_{cap} = 70\ m^2$

$S_{membrane} = 4\ m^2$

The flow rate of the distillate gradually increases at the beginning of the day and it decreases gradually at the end of the day.

The production reached its maximum value for the month of June.

Productivity for four typical days ranges from 250 kg on 21 December to 750 kg on 21 June

Conclusions

- Dynamic modeling of the membrane module.
- Development of a global model describing the operation of the installation witch presents a satisfactory agreement with the experiment.
- A parametric study showed that the vacuum pressure and salinity are two factors greatly affecting the productivity of the membrane and the increase of the feed rate will improve the production of the module.

Perspectives

- ✓Determining the optimal operating conditions and realization of a energetic study of the pilot.
- ✓Study of systems for the recovery of energy and the determination of specific energy consumption.

Thank you for your attention