

ENC-2020-0471

**NUMERICAL ANALYSIS OF THE DESALINATION PROCESS BY
THERMAL MEMBRANE AND USING SOLAR ENERGY AS A WAY OF
ACTIVATION**

Gabriel Araújo de Albuquerque Simões

DEM, Universidade Federal da Paraíba, João Pessoa, Brasil. Cidade Universitária, s/n - Castelo Branco III, João Pessoa - PB, 58051-085
gabriel.adeas@gmail.com

Álvaro Augusto Soares Lima

PPGEM, Universidade Federal da Paraíba, João Pessoa, Brasil. Cidade Universitária, s/n - Castelo Branco III, João Pessoa - PB, 58051-085
alvaroaugusto_18@hotmail.com

Carlos Antonio Cabral dos Santos

DEM, Universidade Federal da Paraíba, João Pessoa, Brasil. Cidade Universitária, s/n - Castelo Branco III, João Pessoa - PB, 58051-085
carloscabraldosantos@yahoo.com.br

Alvaro Antonio Ochoa Villa

DACI/IFPE, Instituto Federal de Pernambuco, Recife, Brasil. Av. Prof. Luís Freire, 500 - Cidade Universitária, Recife - PE, 50740-540
ochoaalvaro@hotmail.com

José Ângelo Peixoto da Costa

DACI/IFPE, Instituto Federal de Pernambuco, Recife, Brasil. Av. Prof. Luís Freire, 500 - Cidade Universitária, Recife - PE, 50740-540
angelocosta@recife.ifpe.edu.br

Héber Claudius Nunes Silva

DACI/IFPE, Instituto Federal de Pernambuco, Recife, Brasil. Av. Prof. Luís Freire, 500 - Cidade Universitária, Recife - PE, 50740-540
hebernunes@recife.ifpe.edu.br

Renan Gonzaga Silva dos Santos

DEM, Universidade Federal de Pernambuco, Recife, Brasil. Av. da Arquitetura, s/n - Várzea, Recife - PE, 50740-550
renang@chesf.gov.br

Abstract. *Water scarcity is a reality in different parts of the world, including the Brazilian Northeast, which every year suffers from a lack of water due to lack of rain or the characteristic of water (the presence of salts) that makes it inappropriate for human consumption. Therefore, this work presents a study on the desalination process using the Thermal Membrane Distillation technique using solar energy as a source of activation. A numerical analysis of the system was performed using the Engineering Equation Solver platform and an estimate of the number of modules to serve a city with 50,000 inhabitants with pure water. Among the main conclusions, it is possible to highlight the possibility of producing 2.6 L/day with a 0.14 m² solar collector and the efficiency of the presented process, which proved to be promising and especially suitable for applications with little or no use of electricity, as in the case of the use of thermal waste.*

Keywords: *desalination, thermal membrane distillation, simulation*

1. INTRODUCTION

The lack of drinking water has been one of the challenges of humanity since its beginnings and climate change has been affecting the rain cycles around the world, further aggravating the problems of water availability in regions such as the hinterland of the Brazilian northeast, where often don't have treated water at your disposal and, when present, its availability is scarce.

Among the alternatives to supply the demand for drinking water is the drilling of artesian wells or the storage of water in dams, but often the water extracted from these places has high levels of salts, making it unsuitable for use, where according to Souza (2006) the water used for irrigation with salt levels above 2g per liter of water causes a drop in agricultural production, while levels above 1g make this water unsuitable for human consumption.

One of the alternatives to make this water suitable for consumption is to carry out the desalination process. This process can occur through the evaporation of water through the burning of a fossil fuel, firewood or through solar energy and its subsequent condensation. The use of the first two methods is inappropriate both from the point of view of logistics and the emission of pollutants. Therefore, the use of solar energy to perform this process has been gaining space and one of the processes that can work using solar energy as a means of activation is the thermal membrane desalination that was initially introduced in the 80s (Silveira, 2015).

Among the desalination processes, those that do not use the membrane and those that use it can be highlighted. The membranes are characterized by being hydrophobic, generating a liquid/vapor interface at the entrance of the pores. Among the processes that make use of the membrane are those of direct contact, air gap, reverse osmosis and electro dialysis.

Therefore, this work aims to analyze, through a numerical study, the use of the thermal membrane desalination process with an air gap activated by solar energy to feed a city with up to 50,000 inhabitants.

2. MODEL

The model analyzed is composed of a solar collector, hot water storage tank, heat exchanger, a thermal membrane desalination system with an air gap, a distillate tank and a feed tank as shown in Fig. 1.

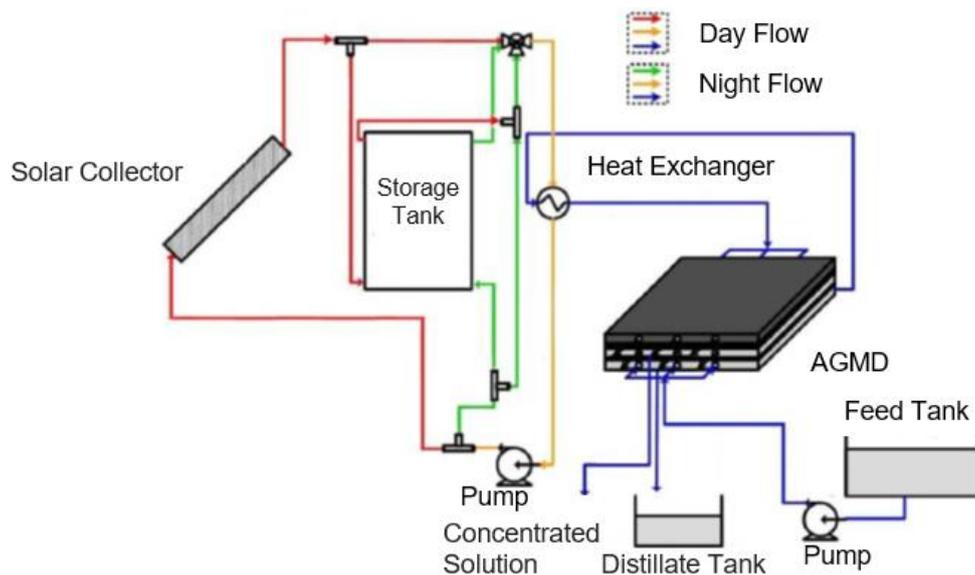


Figure 1: Outline of a desalination process

Source: Adapted from Chang, Lyu, Tsai, Chen, Cheng e Chou (2012)

In the model, the solar collector was adopted as a source of thermal energy, 70% of the water coming out of the collector is directed to the storage tank, while the remaining 30% is directed to the heat exchanger that leads to the air gap membrane desalination module (AGMD). The hot water in the storage tank is intended to keep the system running overnight.

The desalination system adopted in this work is that of an air gap membrane. This system consists of three channels, the first drains water with a high concentration of salts at high temperature, the second, separated from the first by a hydrophobic membrane where the desalinated water that flows through the membrane in the form of steam will flow. The

third channel is parallel to the others and separates from the second through a solid wall, inside this channel drains water with high levels of salts before being heated in the solar collector as described in Fig. 2

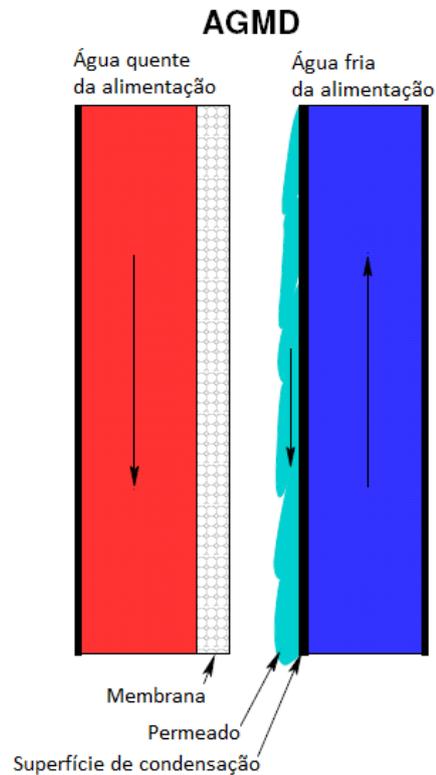


Figure 2: Scheme of operation of an AGMD

Source: adapted from Koschikowski, 2011.

The components of the system were analyzed using the formulation of control volume applied to each component of the system, with the conservation equations applied to them resolved through the EES. Equation 1 shows the energy balance applied to the solar collector.

$$\frac{\partial T_{f,CS}}{\partial t} = -L_{CS} \frac{m_{f,CS}}{M_{f,CS}} \frac{\partial T_{f,CS}}{\partial x} + \frac{A_{CS} \eta_{opt} I(t)}{M_{f,CS} C_p} \quad (1)$$

Where:

$\frac{\partial T_{f,CS}}{\partial t}$: Temperature variation of the fluid flowing into the solar collector

$m_{f,CS}$: Flow of liquid in the solar collector

$M_{f,CS}$: Liquid mass in the solar collector

A_{CS} : Solar collector area

η_{opt} : Optical efficiency

$I(t)$: Time-varying solar radiation

In turn, the energy balance equation for the storage tank is provided by Eq. 2, assuming the flow of the buffer type.

$$\frac{\partial T_{f,TE}}{\partial t} = -H_{TE} \frac{m_{f,TE}}{M_{f,TE}} \frac{\partial T_{f,TE}}{\partial x} \quad (2)$$

Where:

$\frac{\partial T_{f,TE}}{\partial t}$: Variation of fluid temperature in the storage tank

$m_{f,TE}$: Mass flow of fluid inside the storage tank

$M_{f,TE}$: Mass of fluid in the storage tank

H_{TE} : Storage tank height

Considering a countercurrent heat exchanger, with the fluid at elevated temperature coming from the solar collector and the storage tank and the cold fluid from the desalination module and still considering the flow of the buffer type, we have the energy balance provided by Eq. 3 and Eq. 4.

$$\frac{\partial T_{f,TC,FQ}}{\partial t} = L_{TC} \frac{m_{f,TC,FQ}}{M_{f,TC,FQ}} \frac{\partial T_{f,TC,FQ}}{\partial x} - \frac{A_{TC} U_{TC}}{M_{f,TC,FQ} c_{p_f}^L} (T_{f,TC,FQ} - T_{f,TC,FF}) \quad (3)$$

$$\frac{\partial T_{f,TC,FF}}{\partial t} = -L_{TC} \frac{m_{f,TC,FF}}{M_{f,TC,FF}} \frac{\partial T_{f,TC,FF}}{\partial x} + \frac{A_{TC} U_{TC}}{M_{f,TC,FF} c_{p_f}^L} (T_{f,TC,FQ} - T_{f,TC,FF}) \quad (4)$$

Where:

FQ: Hot fluid

FF: Cold fluid

$\frac{\partial T_{f,TC}}{\partial t}$: Temperature variation of the fluid in the heat exchanger

$m_{f,TC,FQ}$: Mass flow in the heat exchanger

$M_{f,TC,FQ}$: Mass of fluid in the heat exchanger

$A_{TC} U_{TC}$: Product of the global heat transfer coefficient area

For the desalination module, the equations that describe the energy balance are described in Eq. 5, Eq. 6 and Eq. 7 respectively.

$$\frac{dm_{f,MD,FQ}}{dx} = -N_{mem} M M_a C_{mem} \quad (5)$$

$$\frac{dm_{f,MD,P}}{dx} = -N_{ba} M M_a C_{mem} \quad (6)$$

$$N_{mem} = N_{ba} \quad (7)$$

Where:

FQ: Hot fluid

P: Wall

$\frac{dm_{f,MD,FQ}}{dx}$: Variation of mass flow in the desalination module

N : Molar flow

mem: Membran

ba: Breath of air

Mass flows are defined through the effective mass transfer coefficients and through the pressure difference between the membrane, Eq. 8, and the air gap, Eq. 9. The transfer coefficient and mass of the membrane, Eq. 10, was defined using Knudsen diffusion, Eq.12 and molecular diffusion. For the air gap coefficient, Eq. 9, only molecular diffusion was considered.

$$N_{mem} = \frac{k_{mem}}{RT_{mem}} (P_{a,m1}^{sat} - P_{a,m2}) \quad (8)$$

$$N_{ba} = \frac{k_{ba} P_{ba}^T}{RT_{ba} P_{ar,ml}} (P_{a,m2} - P_{a,p}^{sat}) \quad (9)$$

$$k_{mem} = \frac{\varepsilon}{\tau} \left[\frac{1}{1/D_K + y_{ar,ml}/D_m} \right] \frac{1}{\delta_{mem}} \quad (10)$$

$$k_{ba} = \frac{D_m}{\delta_{ba}} \quad (11)$$

Where:

k : Mass transfer coefficient

P : Pressure

R : Gas constant

$\frac{\varepsilon}{\tau}$: Ratio between porosity and tortuosity

$y_{ar,ml}$: Logarithmic mean of the change in the molar fraction of air

D_m : Molecular diffusivity

While Knudsen diffusion coefficient is provided by the Eq. 12

$$D_k = \frac{d_p}{3} \sqrt{\frac{8R_g T}{\pi M M_a}} \quad (12)$$

3. The input data used for the simulation are shown in Tab. 1, while the incident solar radiation profile is shown in Fig.

Table 1: Input data used for the simulation

Solar collector	
Weight of water, $M_{f,CS}$	1,4 kg
Width, L_{CS}	0,19 m
Length, C_{CS}	0,76 m
Thermal storage tank	
Weight of water, $M_{f,TE}$	3 kg
Tank height, H_{TE}	0,28 m
Heat exchanger	
Area, A_{TC}	0,005 m ²
Length, L_{TC}	0,15 m ²
Overall heat transfer coefficient, U_{TC}	280 W/m ² K
Membrane distillation module	
Hot fluid channel height, H_{FQ}	2 mm
Cold fluid channel height, H_{FF}	2 mm
Air gap thickness, E_{BA}	2 mm
Membrane area, A_m	0,05 m ²
Membrane width, L_{mem}	0,25 m
Membrane length, C_{mem}	0,2 m
Total membrane thickness, δ_{MEM}	130 μ m

Membrane layer thickness, δ_{mem}	30 μm
Membrane material	PTFE (poroso); PP (apoiando)
Membrane pore diameter, d_p	0,1 μm
Membrane porosity, ϵ	0,72
Membrane tortuosity, τ	1,39
Others	
Mass flow in the solar collector	4,9 kg/h
Mass flow on the hot side of the heat exchanger	4,9 kg/h
Mass flow in the module	2,5 kg/h
model slope angle	27°
Weight of water on the hot side of the heat exchanger	0,75 kg
Weight of water on the cold side of the heat exchanger	1,0 kg
Optical coefficient of the solar module	0,75

Source: Adapted from Chang et al., 2012.

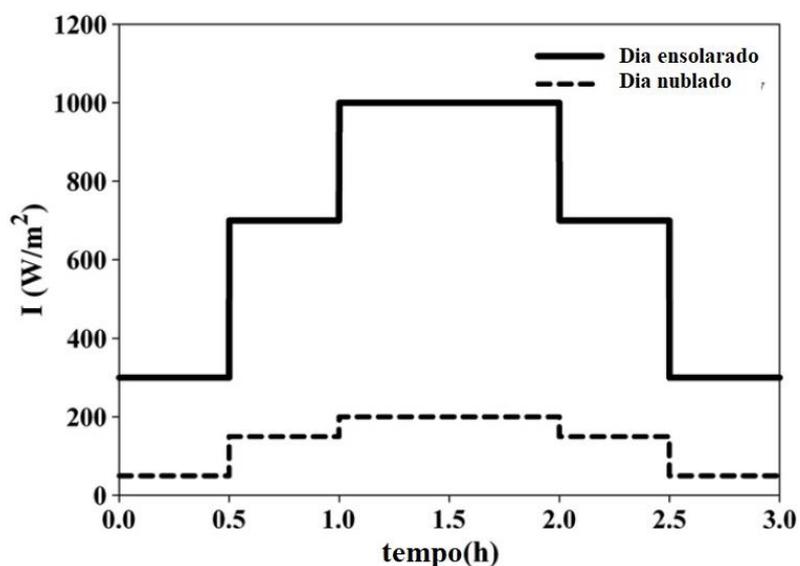


Figure 3: Incident solar radiation profile

Source: Adapted from Chang et al., 2012.

Results

As a starting point of the analysis, the model adopted was validated using the work of Chang et al. (2012). The results of the validation are shown in Fig. 4 for the solar collector, Fig. 5 for the storage tank, Fig. 6 for the hot side of the heat exchanger, Fig. 7 for the hot fluid entering the module and Fig. 8 for the production index distilled water. The differences found between the two studies can be associated with the error present in the method adopted in the present study and the fact that the system was considered thermally isolated.

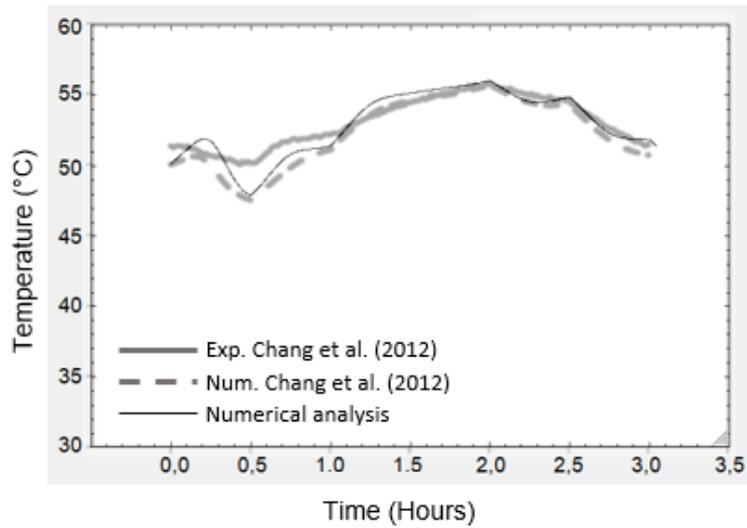


Figure 4: Validation of temperature distribution in the solar collector

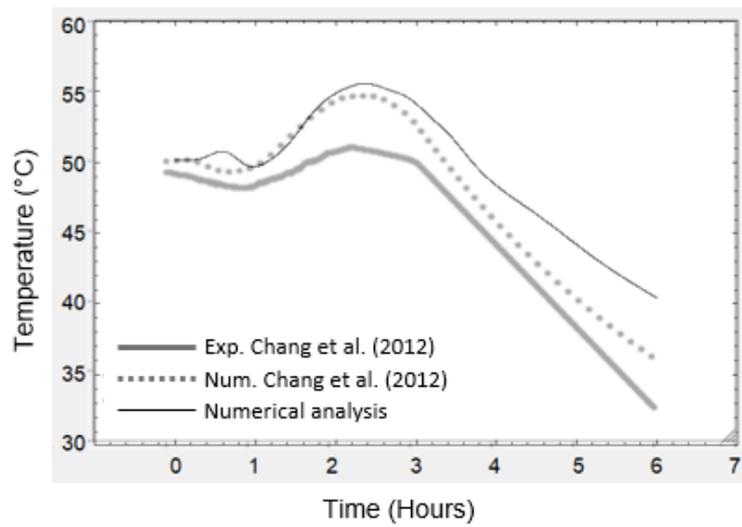


Figure 5: Validation of temperature distribution in the storage tank

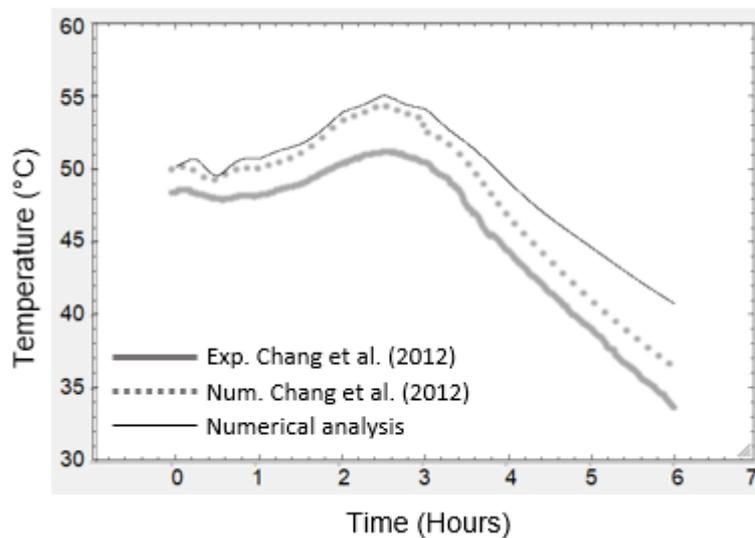


Figure 6: Validation of temperature distribution hot side of the heat exchanger

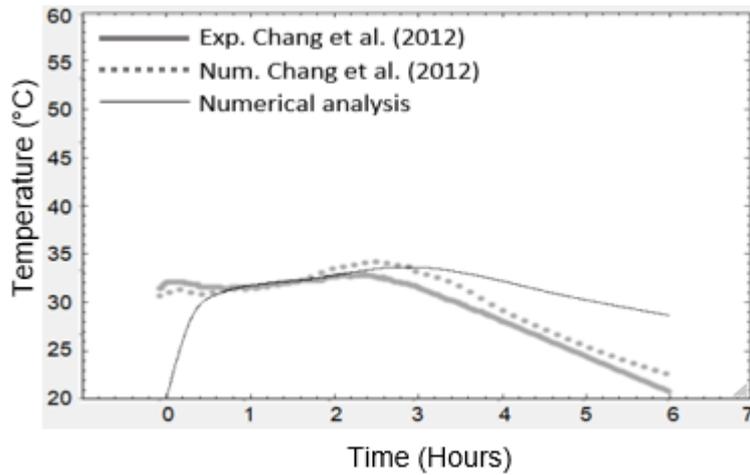


Figure 7: Validation of temperature distribution for hot fluid entering the module

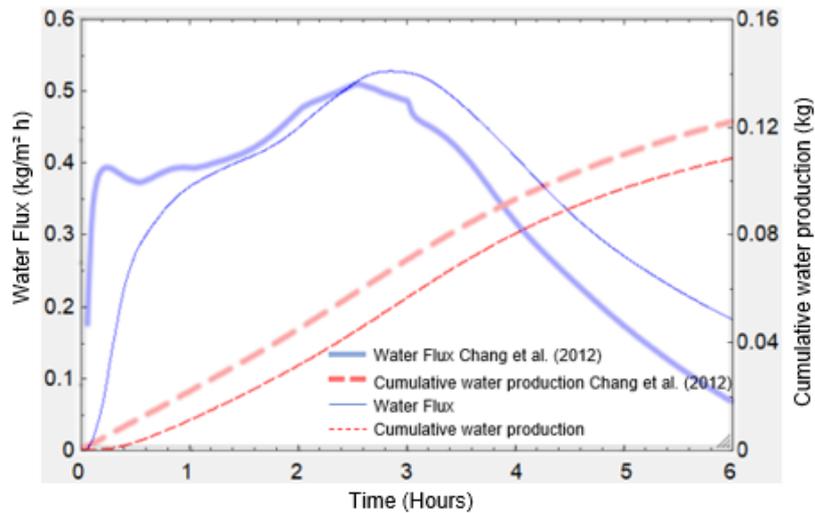


Figure 8: Validation of production index distilled water

The model was validated, where it was befitting to the results found in the literature, a parametric analysis was carried out, where the water circulation temperature was varied in the cycles of the solar collector and the desalination module for two different areas. The results are presented in summary form in Tab. 3.

Table3: Parametric analysis

Simulation	Features	Production	Problems
1	Heating loop: 80°C Module loop: 20°C Solar collector: 0,14 m ²	2,6 L/day	Initial temperatures not maintained for the next cycle.
2	Heating loop: 50°C Module loop: 20°C Solar collector: 0,07 m ²	0,6 L/ day	Low production; Initial temperatures not maintained for the next cycle.
3	Heating loop: 50°C Module loop: 20°C Solar collector: 0,14 m ²	0,9 L/ day	Low production
4	Heating loop: 80°C Module loop: 20°C Solar collector: 0,07 m ²	1,6 L/ day	System fails to maintain initial temperatures.

From Tab. 3, it is possible to observe from the comparison between simulations 1 and 3 that the increase in the temperature of the circuit that passes through the solar collector leads to an increase in production, with a 60% increase in temperature (50° to 80°) led to an increase of approximately 190% in the production of distilled water.

On the other hand, when comparing simulations 2 and 3, the increase in the area of the solar collector leads, as in the previous comparison, to an increase in the production of clean water. In this case, a 50% increase in the area of the solar collector (0.07 to 0.14) led to a 50% increase in the amount of distilled water.

Comparing the previous analyzes, due to the gain in production with the increase in the temperature of the collector circuit, it becomes more advantageous to invest in solar collectors that reach higher temperatures.

Conclusions

The work developed was consistent with the works found in the literature, even using simplifications.

It can also be highlighted the gain of approximately 190% in the production of distilled water due to an increase in the temperature of the system.

Finally, it can be concluded that it is more advantageous to invest, from the point of view of system performance, in a solar collector capable of reaching higher temperatures instead of just increasing the area of the exchanger, thus obtaining greater gains.

3. ACKNOWLEDGEMENTS

The second author thanks the Capes for the doctorate's and master's degree scholarship and also the Post-Graduate Program in Mechanical Engineering at UFPE/UFPA for the opportunity to develop his project.

4. REFERENCES

CHANG, Hsuan; LYU, Shao-Gang; TSAI, Chih-Ming; CHEN, Yih-Hang; CHENG, Tung-Wen; CHOU, Ying-Hsiu. Experimental and simulation study of a solar thermal driven membrane distillation desalination process. *Desalination*, [S.L.], v. 286, p. 400-411, fev. 2012. Elsevier BV.

SOUZA, Luiz F. Dessalinização como Fonte Alternativa de Água Potável. *Revista Norte Científico*, v. 1, n. 1, p. 84-97. Dez. de 2006.

SILVEIRA, Ana P. P. et al. Dessalinização de Águas. Ed. Oficina de Textos. São Paulo. 2015.

KOSCHIKOWSKI, Joachim. Entwicklung von Energieautark Arbeitenden Wasserentsalzungsanlagen auf Basis der Membrandestillation Fraunhofer Verlag. 2011.

5. RESPONSIBILITY NOTICE

The authors are the only responsible for the printed material included in this paper.