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AUTONOMOUS HDH SOLAR SEAWATER DESALINATION

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Abstract

The solar-driven humidification-dehumidification (HDH) cycle is a type of solar thermal distillation technology that works based on the vapor absorption properties of air combining an evaporation process (humidification) with a condensation process (dehumidification). The design of the system allows the integration in pilot units of small and medium size adjusted to the final needs of fresh potable water and with the possibility of relying only on solar energy. This paper describes an HDH solar unit designed and constructed in Portugal in the framework of project SELFWATER. A MATLAB model based on energy and mass balance equations in the evaporator and condenser was developed and the results are compared with preliminary experimental tests performed in the constructed prototype at LNEG *thermal desalination test facility. This comparison s*hows a good agreement between the model and the test results mainly in terms of the Gain Operating Ratio (GOR) and Performance Rate (PR) following also the results of similar devices taken from a literature review.

Keywords: Desalination; Humidification; Dehumidification; Solar Energy; Small-scale water production.

1- State of the art

Demographic pressure, economic and regional conflicts joined with the effects of global warming have been causing a trend of water scarcity worldwide. So far some conventional desalination technologies have been an alternative for some large-scale market economies but not shared with other regions of the world in social and economic process development (El-Dessouky et al., 2010). These are energy intensive technologies highly dependent on fossil fuels and typically causing environmental hazards due to discharge of brine on the coastline. Additionally most of these regions had the main difficulty in getting or maintaining their infrastructure of electrical power and water distribution for most of the population outside the major cities (PRODES, 2010).

Several countries from Mediterranean basin, African coast and Latin America have in own agenda the urgent demand for low-cost solutions which minimize water shortages, mainly through decentralized and small scale desalination technologies using renewable energy sources that could achieved sustainable drinking water supply in a cost effective way (Farid et al., 1996). For Portugal and Spain the desalination of both brackish water and seawater is a solution to the recurrent water shortages in some islands or coastal regions as for example Mediterranean and Atlantic Islands.

In some of these regions projects were developed through photovoltaic solar energy to power reverse osmosis units for the production of water for human consumption, but the dissemination of this technology is still limited due to relative high cost of PV modules and specific maintenance problems of RO systems. Even though the RO process is the most economical desalination system, the specific cost of water production systems is much higher than for large-scale systems and cannot allow the installation for small-scale applications (less 100 m^3/day) (Müller-Holst, 2007).

A alternative approach is the use of solar energy to develop thermal desalination technologies in an efficient and low-cost way. The current state of development of solar thermal desalination shows the existence of previous studies associated with a production on a limited scale with improved experience but no better results. Experimental research efforts need to be improved having in mind optimized design, construction and operation of new pilot plants, but attempts to commercialize or to become part of the activities of water and energy public authorities still lag behind conventional desalination.

A possible evolution of the simple one stage Solar still is the concept of solar-driven humidification-dehumidification desalination cycle (HDH). This technology appears to be promising for small-scale seawater desalination even the few field results point to relatively high energy consumption. State of the art

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solar of thermal desalination configurations and experimental prototypes resume practical coupled applications with solar pond with salt gradient in Mediterranean basin.

2 – Introduction

The solar-driven humidification-dehumidification (HDH) cycle is a type of solar thermal distillation technology that works based on the vapor absorption properties of air combining an evaporation process (humidification) in a way separated from the condensation process (dehumidification).This technology is the simplest approach to the natural water cycle and in its most basic version the HDH system has only three components: evaporator (humidifier), condenser (dehumidifier) and an heat transfer system that can be based on solar energy, waste heat or geothermal energy..

In the one stage simple solar still the processes of solar energy absorption the salt water evaporation and condensation and heat recovery are conditioned inside a single chamber while with the HDH cycle these functions are separated into distinct components. This distinguishes the evolution of HDH desalination concept by allowing increased thermal efficiency. In this way design and engineering could optimized the HDH cycle separating the components of the solar heating system or the evaporation and condensation cycles

The HDH cycle desalination technology has been investigated since the mid-90 (Farid et al., 1996; Joyce et al., 1998; Nawayseh et al., 1999) and several variations of HDH cycle continued to be reported and in operation (Mathioulakis et al., 2012). With some experimental realizations but few commercial applications the HDH technology prototypes applied to small-scale decentralized water production needs additional research and development to improve system efficiency in comparison with other desalination processes as it show in table 1, in order to reduce their installation and maintenance costs and ultimately reducing the cost of fresh water produced.

Desalination Process	Specific energy consumption [kJ/kg]	Performance *r* [dim.]	References
Evaporation stage (solar still watercone)	2300	0,98	(Maurel,1981)
HDH (Solar) (with thermal recovery)	792	2,8	(Baumgartner,1991)
MEH (multiple stages)	384	6,0	(Maurel,1981)
VC (thermal cycle)	233	9,5	(Joyce,1992)
MSF (multiple stages)	185	12,2	(Maurel,1981)
ED	108	21	(Maurel,1981)
RO	43	52,5	(Maurel,1981)
RO (with pressure recovery)	29	78	(Maurel,1981)

Table 1- Comparison of specific energy consumption and performance of distinct desalination processes.

Although there are many known variations of the HDH cycle this technology allows different classifications, by energy source used, by mass and energy transfer processes or by heat exchange process. Solar energy is the most significant source of energy that now days it is explored and more promising results will be expected for autonomous desalination small-scale plants with renewable energy systems. Classification by mass and energy transfer processes is related to two main HDH configuration (Narayan et al., 2010): the closed-water open-air (CWOA) cycle where air runs by a in-out circuit and is heated, humidified and dehumidified; or the closed-air open-water (CAOW) cycle, that is used in the prototype described in this work, different from CWOA cycle because air flows in a closed loop humidifier-dehumidifier and seawater flows at in-out cycle. In both configurations air can be circulated by either natural or forced circulation but featuring results didn´t agree about the best running efficiency (Nawayseh et al., 1999; Al-Enezi et al., 2006; Müller-Holst, 2007).

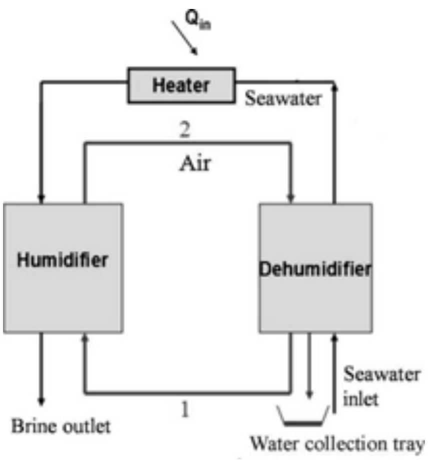

Fig. 1 – HDH basic cycle CAOW configuration with its main components: (a) an air and/or the water heater, which can use the solar energy power Qin; (b) a humidifier as water vapor evaporator; (c) a dehumidifier as water vapor condenser (Narayan et al., 2010).

3. Prototype chamber description

The prototype here described was developed in the framework of a Portuguese and structural funds supported project called SELFWATER. This project aimed to develop a desalination based on humidification-dehumidification technology (HDH) cycle powered by solar thermal energy, for the purpose of decentralized drinking water supply and energy autonomy for small communities. The design of the prototype followed a modular type concept for the integration of pilot units of small and medium scale size adjusted to different needs of potable water. The device is prepared for an innovative pilot plant concept that will include low temperature solar thermal collectors and PV systems for the electric consumption in order to reach total energy autonomy.

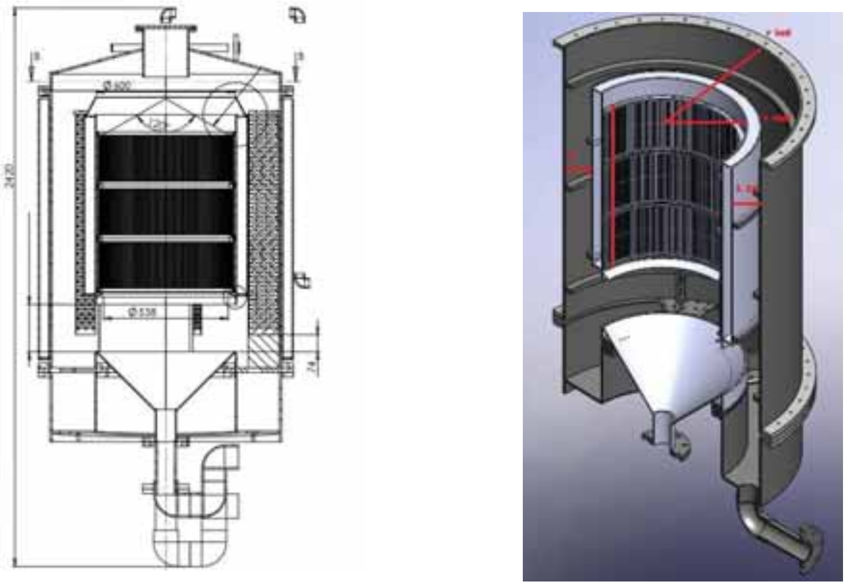

Fig. 2 – Schematic drawings and exploded view of SELFWATER HDH prototype (LNEG, 2012).

The SELFWATER HDH cycle prototype consists of two circular concentric chambers (Figure 2). The body of the HDH desalination prototype comprises a sealed polyethylene (LPPE) cylinder with one cubic meter nominal volume with external 30 mm thick polyurethane insulation: the inner chamber acts as an evaporator system through a spray of heated brackish or salt water on top of stacked baskets with filler components based on synthetic or thermoplastic material with thermal, mechanical and chemical properties suitable for potable water use. These filler components are designed to increase the specific surface area of contact of the water sprayed increasing the mass transfer and thus increasing water vapor that will condensate in the condensation chamber.

The cylindrical outer chamber has 300m of multilayer thermoplastic PEX coiled pipe allowing the dehumidification process through condensation of water vapor which in fact is an air-water heat exchanger allowing pre-heating cold salt water by recovering latent heat of condensation. The evaporation chamber operates with typical low values of salt water temperature below 85°C.

The heated salt water is introduced in the evaporation chamber through a polypropylene (PP) circuit pipe plus a flexible rubber tubing both suitable for low temperature and high sodium chloride salinity. Inside the body cover polypropylene pipe assumes a dripper configuration that will cover the entire inner chamber section. The salty solution (brine) rejected of the evaporation process is collected for local pickup after passing a siphon used for leak tightness of the system. The distilled water produced during the desalination process is collected directly in the bottom of condensation chamber.

Fig. 3 – Assembled views of SELFWATER HDH prototype connected to the thermal test facility at LNEG laboratory. Left: stacked baskets with synthetic fabrics; Right: HDH prototype body with circular concentric chambers (condenser and evaporator).

4. Innovative test facility

SELFWATER project designed and installed a thermal desalination test facility that enables to simulate different heating profiles of the salt water including the simulation of a solar thermal installation. A storage tank allows high thermal capacity to run long test cycles and deliver either constant temperature or variable temperature according to a simulated solar thermal collector behavior. This flexibility allows the testing of different desalination chambers under real conditions. The desalination test facility comprises a hot water system with a hydraulic kit with forced circulation and temperature control through a PLC.

The components of the test facility are as follows (Figure 4): three tanks for artificial seawater and brine disposal [DO1-D03]; HDH desalination prototype with two concentric chambers; hydraulic skid with two circuits to flow cold brine (C1-M2-T1-Q1) and hot brine (C2-M4-Q2-Q4); a cascading electric heating system to maintain stratification temperature levels; a storage 1000 liters water tank (AC01), with an logic PLC to simulate the rate of heating system.

The thermal facility has a specific monitoring system connected to type T thermocouples and PT100 resistance temperature probes and water flow meter connected to an Agilent 34970A data logger model, with Bench-Link software and LABVIEW virtual interface environment that updates real-time measured parameters during performance tests (Figure 5).

Fig.4 - Solar thermal desalination test facility to operate and testing solar desalination prototypes at LNEG laboratory.

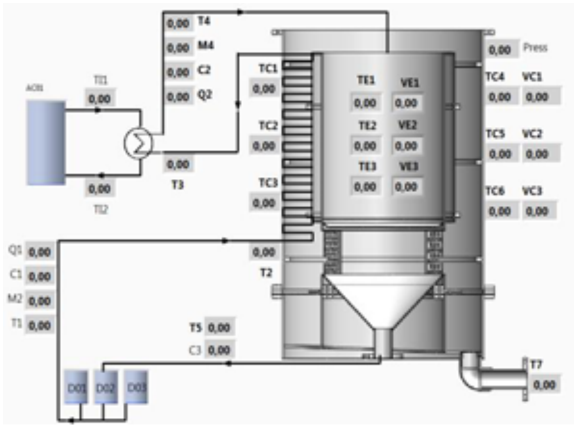

Fig. 5 - Interface NI LABVIEW virtual environment that post real-time measured parameters during performance cycle at thermal test facility.

5. Mathematical model

The mathematical model of the system is based on energy and mass balance equations for both evaporator and condenser chambers. Additionally balanced equation for air circulation was used to implement the mathematical model of the device. Basic assumption of the model assumes a closed-loop air between evaporator and condenser and open-loop seawater on evaporator at steady-state conditions. A sectional drawing of SELFWATER HDH CAOW prototype is showing at Figure 6 with schematic evaporator (center view) and condenser (side view) and control parameters of mass flow rates and operational temperatures for air and water processes cycle. A system of equations were solved using MATLAB 4^{th} order range kutta with accuracy of 0.001.

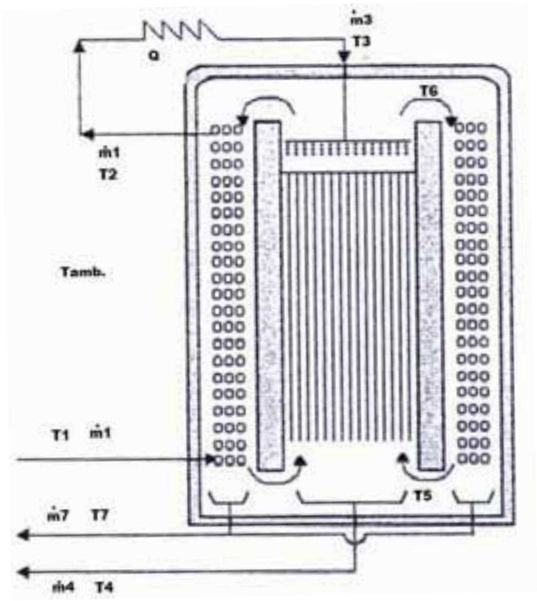

Fig. 6 – SELFWATER HDH CAOW schematic cycle with main control parameters - temperature and mass flow – from evaporator (m3,m4, T3, T4, T5 and T6) and condenser (m1,m7, T1, T2 and T7. The seawater gets pre-heated in the process (m1, T1 and T2) and is further heated in a solar collector (Q) (Joyce, 1998).

6. Results and discussion

Preliminary tests processes at evaporator and condenser chambers had been performed with different types of humidification packing baskets combined with distinct area for coiled thermoplastic pipe at dehumidification process. These preliminary results have contributed substantially to comprehend and adjust the steady-state condition of the MATHLAB model. Each experiment lasts several hours with heated seawater at permanent boundary conditions {T_3=73ºC; $\dot{m}_3$=100 l/h; 35mS/cm seawater conductivity. An example of the thermal behavior of principal parameters of the CAOW cycle in terms of gap temperatures in the distinct parts of the HDH prototype is represented at Figure 7. Apart the transient processes of the first two hours, separate thermal processes at humidifier and dehumidifier chambers assumed energy and mass model as expected at the mathematical model.

Temperature gap T_3-T_4 between mass flows rate from feed water to brine are closely to 40ºC and shows lower thermal performance for the evaporator that will be expected. Gap temperature T_3-T_6 less than 30ºC represents the transferred energy due to evaporation by means of sensible and latent heat. More expressive drive motion for the CAOW cycle will be expected but relative pressure drop across the condenser was confirmed. Better performance is achieved to dehumidification process due to meaningful gap temperature T_6-T_5 of 20ºC and increasing from top to down condenser evident natural air convection. This outcome follows the increasing tendency to expand latent heat recovery gap temperature T_3-T_4 on the condenser and confirms the good prospect of the HDH as solar desalination promising technology.

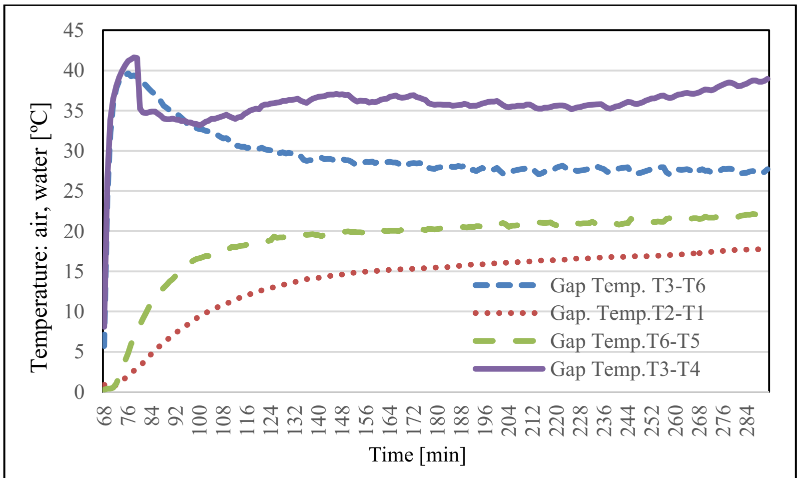

Fig. 7 – Experimental results evaluated gap temperature in coupled temperatures related to heat and mass transfer in humidification and dehumidification processes. Boundary conditions: T_3 = 73ºC; m_1=m_3=100 l/h; 35mS/cm seawater conductivity.

Experimental results shows that salt recovery ratio (R) reach 97% with performance ratio (PR) around 6%. Rejected brine with high conductivity around 43mS/cm and permeate salinity measurements under 1000µS/cm are both the confirmation of the effectiveness of the desalination process. The obtained permeate water conductivity is in good agreement with the international standard recommendations for drinkable water.

Numerical results plotted in figure 9 represent estimated performance GOR parameter for the HDH cycle, the relation between latent heat of evaporation of the water produced to the net heat input to the cycle, related to air mass flow rate variation grouped at three levels of heating input for feed water. Experimental results at desalination facility were obtained with a heating power of 3250W for a distinct mass flow rates but no conclusion yet could be done about measured GOR.

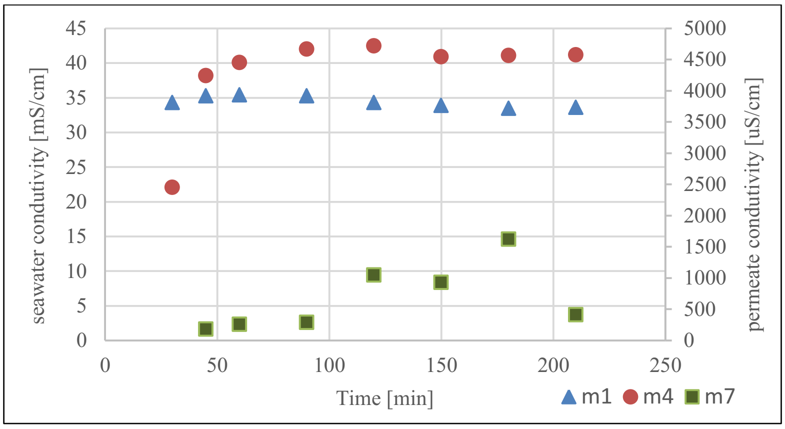

Fig 8 – Permeate flow (m_7) versus feeding seawater flow (m_1). Experimental results evaluated salt recovery ratio to 97% and performance ratio about 6%. Boundary conditions: T3 = 73ºC; m_1=m_3=100 l/h; 35mS/cm seawater conductivity.

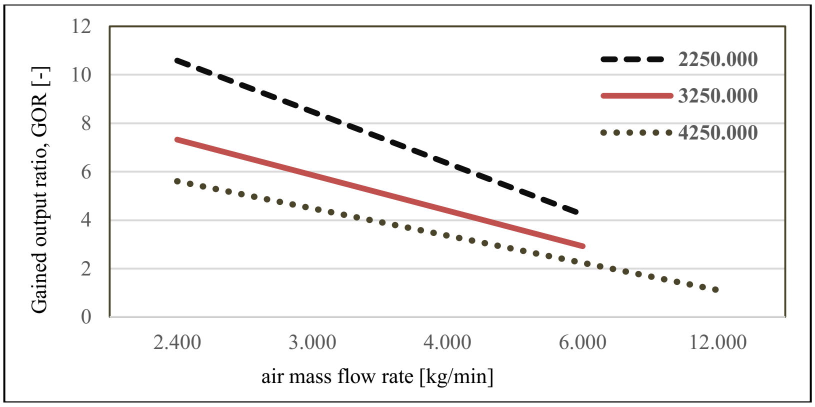

Fig.9 – Model sensitivity analysis of GOR related to mass flow rate $\dot{m}_1$. Net heat input power stages: 2250, 3250 and 4250 W.

Future mathematical model modifications will consider different filler elements at the humidifier in order to evaluate the implications of feed water temperature and mass flow rate on the calculation of GOR of the SELFWATER system. Possible modifications on cycle configuration can include forced air convection to improve Performance Ratio.

7. Conclusion

SELFWATER project HDH based prototype showed good performance in terms of produced water quality and appears to be a promising technology for small-scale seawater desalination. It follows a modular type concept in order to facilitate the integration in pilot units of small and medium scale size adjusted to the need of potable water in small communities.
The setup of a thermal desalination test facility enabling the analysis and monitoring of solar driven salt and brackish water purification, showed the importance of this device for testing different desalination chambers under real conditions.
A mathematical model based on MATLAB platform was also an important simulation tool developed in the framework of project SELFWATER. Preliminary results were obtained for salt recovery ratio (R) reaching 97% and performance ratio (PR) reaching 6%. Future mathematical model improvements will include a

dynamic model and forced air convection in order to evaluate the yearly production of the device when connected to solar thermal collectors.

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References

Al-Enezi, G., Ettouney, H.M., Fawzi, N., 2006. Low temperature humidification dehumidification desalination process. Energy Conversion and Management, 47: 470–484.

El-Dessouky HT, Ettouney HM, 2002. Fundamentals of salt water desalination. Elsevier.

Farid, M.M, Al-Hallaj; A.W., 1996. Solar desalination with humidification–dehumidification cycle, Desalination 106: 427–429.

Joyce, A., Pereira, M. C., Loureiro, D. e Oliveira, J., 1992. Dessalinização por energia solar: perspectivas e ensaios preliminares com um sistema multi-efeito, CYTED report, LNETI, Portugal.

LNEG, 2012. Projecto SelfWater "Tecnologias de dessalinização com sistemas solares e o seu estágio de desenvolvimento tecnológico" (in portuguese). QREN confidencial report. LNEG. December 2012. Lisbon. Portugal

Müller-Holst, H., 2007. Solar Thermal Desalination using the Multiple Effect Humidification (MEH) method in Solar Desalination for the 21st Century, Springer, Dordrecht.

Mathioulakis, E., Panaras, G., e Belessiotis, V., 2012. Experience gained through the implementation and operation of a solar humidification—dehumidification desalination plant. Desalination and water treatment, 21: 1-3, 375-384.

Narayan, G.P., Maximus G. St. John, Syed M. Zubair, John H. Lienhard V., 2013.Thermal design of the humidification dehumidification desalination system: An experimental investigation. International Journal of Heat and Mass Transfer, March, Vol. 58, 1–2: 740-748.

Nawayseh, N.K, Farid, M.M., Al-Hallaj, S., Tamimi, A.R., 1999., Solar desalination based on humidification process-Part I. Evaluating the heat and mass transfer coefficients, Energy Conversion Management, 40: 1423–1439

Orfi, J., M. Laplante, H. Marmouch, N. Galanis, B. Benhamou,S. Ben Nasrallah, C.T. Nguyen, 2004.Experimental and theoretical study of a humidification-dehumidification water desalination system using solar energy. Desalination 168: 151-159.

PRODES, Papapetrou, M., Wieghaus, M., & C.Biercamp, 2010. Roadmap for the Development of Desalination Powerd by Renewable Energy. Europe: Fraunhofer Verlag.