Available online at www.sciencedirect.com

ScienceDirect

Energy Procedia 81 (2015) 472 – 481

Energy Procedia

69th Conference of the Italian Thermal Engineering Association, ATI 2014

Design and construction of a desalination prototype based on HD (Humidification-Dehumidification) process

Giuseppe Franchini*, Luca Emilio Padovan, Antonio Perdichizzi

Department of Engineering and Applied Sciences, University of Bergamo, viale Marconi 5, Dalmine (BG), 24044, Italy

Abstract

The paper deals with a low-temperature thermally driven desalination unit exploiting the HD (humidification/dehumidification) process. The system is a closed air cycle unit and is based on a single-effect humidification/dehumidification technique: heated seawater is introduced into the humidification section of a closed tunnel to saturate the circulating air; then the water vapor in moist air separates within the condensation column, where freshwater production takes place.
A HD desalination prototype has been designed, assembled and fully instrumented in order to monitor all physical quantities and to evaluate the performance under different operating conditions. The prototype has been experimentally investigated on a test facility established at the Bergamo University Labs. The results of the measurement campaign are presented and discussed.
A computer code for simulating the desalination process has also been developed and it was validated by the experimental data. The modeling procedure investigates air and water thermodynamic properties across every component and allows to predict the HD desalination unit performance, varying seawater and air flow rates, the heat source temperature level and the heat exchanger surfaces.

Peer-review under responsibility of the Scientific Committee of ATI 2014

Keywords: desalination; renewable energy; low-grade heat

1. Introduction

According to the data from International Desalination Association, the desalination plants worldwide amount to more than 17,000 units, with a global capacity higher than 80 million cubic meters per day. Desalination is being used

* Corresponding author. Tel.: +39-035-205-2078; fax: +39-035-205-2077.
E-mail address: giuseppe.franchini@unibg.it

Peer-review under responsibility of the Scientific Committee of ATI 2014
doi:10.1016/j.egypro.2015.12.121

in about 150 countries worldwide, meeting the water needs of an estimated 300 million people [1]. Most of the production comes from the Gulf Area (Saudi Arabia, 9.17 million m^3/d; UAE, 8.38 million m^3/d) [2]. Commercially, the two most important technologies are based on the RO (about 60% of the global installed capacity) and MSF (about 27%) processes.

Nomenclature

a	surface per unit volume (m^{-1})
D	fresh water production (kg s^{-1})
E_{sp}	specific energy consumption (kWh/m^3)
G	air flow rate (kg s^{-1})
HD	humidification/dehumidification
heat	heating, heater
HX	heat exchanger
k	mass transfer coefficient (kg m^2 s^{-1})
L	sea water flow rate (kg s^{-1})
MED	multiple effect distillation
MSF	multi-stage flash
NVD	natural vacuum desalination
Q	thermal power (W)
RH	relative humidity (%)
RO	reverse osmosis
T	temperature (°C)
V	volume (m^3)

Today, developments in desalination technologies are specifically aimed at reducing energy consumption and cost. Advancements include new and emerging technologies which make use of low grade thermal energy, like MED, solar distillation, HD desalination, NVD and membrane distillation. The desalination industry is also paying a great deal of attention to environmental considerations. Environmental safeguards have become increasingly important in siting and permitting of new plants. In this scenario, the HD desalination technique can play an important role, as it is a suitable solution for small size systems and it can make use of renewable energy or recovered heat.

Water desalination by air humidification and dehumidification has been the subject of many investigations. A large number of papers in the open literature are focused on the simulation of the humidification/dehumidification process. Nawayseh et al. [3] developed a simulation program to describe the performance of HD desalination units and to evaluate the effect of different parameters such as the condenser and humidifier area, as well as the effect of the feed water flow. A steady-state mathematical model was developed by Xiong and Wang [4] to evaluate the mass transfer coefficient at the humidification side. Franchini and Perdichizzi [5,6] presented a computer code simulating the operation of a low-temperature HD system coupled with a LiBr absorption chiller. They demonstrated the feasibility of an integrated cooling-desalination system where a LiBr absorption machine is driven by solar collectors and the low-temperature heat rejected by the chiller is exploited to drive the HD process.

Other published papers deal with the experimental investigation of desalination prototypes based on HD process. Al-Hallaj et al. [7] investigated a solar desalination unit exploiting HD process. In their unit the circulated air by natural or forced convection was heated and humidified by the hot water obtained either from a flat plate solar collector or from an electrical heater. The latent heat of condensation was recovered in the condenser to preheat the saline feed water. Chafik [8] presented the development of a process using the solar energy to heat airflow up to a temperature between 50 and 80°C. The moderate solar heated air is humidified by injecting seawater into the air stream. Later on, the desalted water is extracted from the humid air by cooling it. Using air as a heat carrier and keeping the maximum operating temperature in the process lower than 80°C enables the use of cost effective polymers as construction material. Bouroni et al. [9] experimentally investigated a desalination plant using the aero-evapo-condensation process. The system consists of a falling film evaporator and condenser made of polypropylene. It was designed to work at low temperatures (70–90°C). It was shown that the process can be attractive in the arid and semi-arid areas, which have important resources of hot brackish water, although the energy required by the plant is relatively high.

A solar desalination unit with humidification and dehumidification was presented by Dai and Zhang [10]. Experiments on the unit showed that the performance of the system is strongly dependent on the temperature of inlet salt water to the humidifier, the mass flow rate of salt water, and the mass flow rate of the process air.

A dynamic modeling of a water desalination prototype by solar energy using humidification-dehumidification process was developed and experimentally validated by Ben Bacha [11]: the system employs a field of flat-plate air solar collectors and a field of flat-plate water solar collectors for separately heating air and seawater. A similar system making use of solar air heaters was investigated by Yamali and Solmus [12]: they performed an experimental study on a pilot plant located at Ankara to investigate the influence of different operating conditions.

So, in the recent past many researchers focused their attention on the development of new desalination system based on HD technique, reflecting the strong interest in this technology. The present work aims to give a contribution to the development of innovative and efficient desalination systems harvesting low-grade heat.

2. Humidification/Dehumidification process

The HD process is based on the fact that air can be mixed with important quantities of vapor. When an airflow is in contact with salt water, air extracts a certain quantity of vapor at the expense of sensitive heat of salt water. On the other hand, distilled water is recovered by maintaining humid air at contact with cooling surfaces, causing the condensation of a part of vapor mixed with air. Generally the condensation occurs in another heat exchanger where salt water is preheated by latent heat recovery. An external heat contribution is necessary to drive the system.

The basic cycle consists of heat source, air humidifier and dehumidifier (Fig. 1). A humidifier is used to saturate circulating air. In the condenser the hot humid air goes in contact with the cooled surfaces which make happen the condensation of water vapor and a production of fresh water takes place. The condensation heat is used to preheat the sea water. The HD desalination technique typically operates at ambient pressure with heated sea water temperature included in the range between 70°C and 95°C. The goal of the present work is to explore the operation of the desalination system at lower temperatures, in the range 45-65°C in order to exploit low grade heat sources.

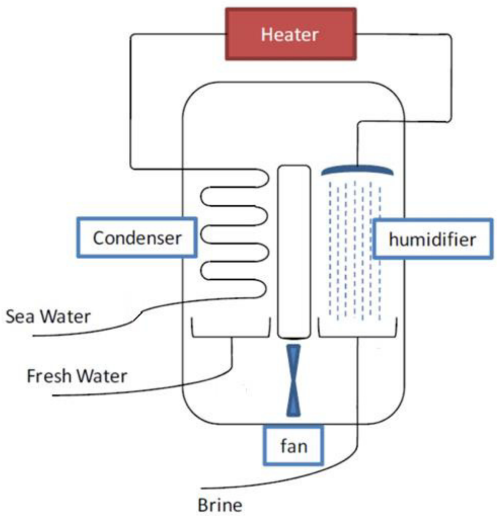


Fig. 1. Scheme of a HD desalination unit.

3. Description of the prototype

A prototype of a HD desalination unit was designed and assembled at the Bergamo University Labs. Fig. 2 shows a 3D rendering of the system and a picture of the prototype on the testing facility. A variable speed blower (visible on the bottom) allows the air to circulate within the closed tunnel. Flow deflectors are used to reduce pressure drops within the circuit. The right-hand vertical column contains the humidification section: here a number of full-cone and hollow-cone nozzles spray the preheated seawater in a countercurrent air stream. The spatial distribution of nozzles was designed to properly direct the water jets and to maximize the contact surface with air. On the top, a demister prevents any water drops to enter the condenser. Freshwater condensation takes place in the two air-to-water heat exchangers, diagonally installed to facilitate the water drop fall. A tank collects the condensate at the bottom of the left-hand column. An optional recuperative heat exchanger is located between the dehumidification and the humidification sections: it is fed by the brine collected at the bottom of the humidifier and it allows to heat the circulating air.

The frame is made of anodized aluminum profiles, providing good mechanical properties and high corrosion resistance. External walls are made of polycarbonate, whose transparency allows to easily observe the physical processes within the air circuit.

The prototype is fully instrumented in order to monitor all physical quantities across each component in the air and water flows. The instrumentation devices are summarized in Tab. 1 with their full scale and accuracy. Air flow rate is evaluated measuring the dynamic pressure within the inlet duct of the blower. A multichannel data acquisition system acquires the input analog signals from the instrumentation devices and a LabView virtual instrument (see Fig. 3) displays and records the test data.

The prototype is installed on a testing facility equipped to carry out experimental investigations under different operating conditions. Two temperature controllers with 70 kW total thermal power allow to heat the seawater flow rate up to 95°C and to regulate the water temperature entering the humidifier at the set-up level. A 1000 liter tank feeds the desalination unit; the water collected at the bottom of the humidification column is sent to a dry air cooler with 60 kW cooling capacity and then it is recirculated within the plant (see Fig. 4).

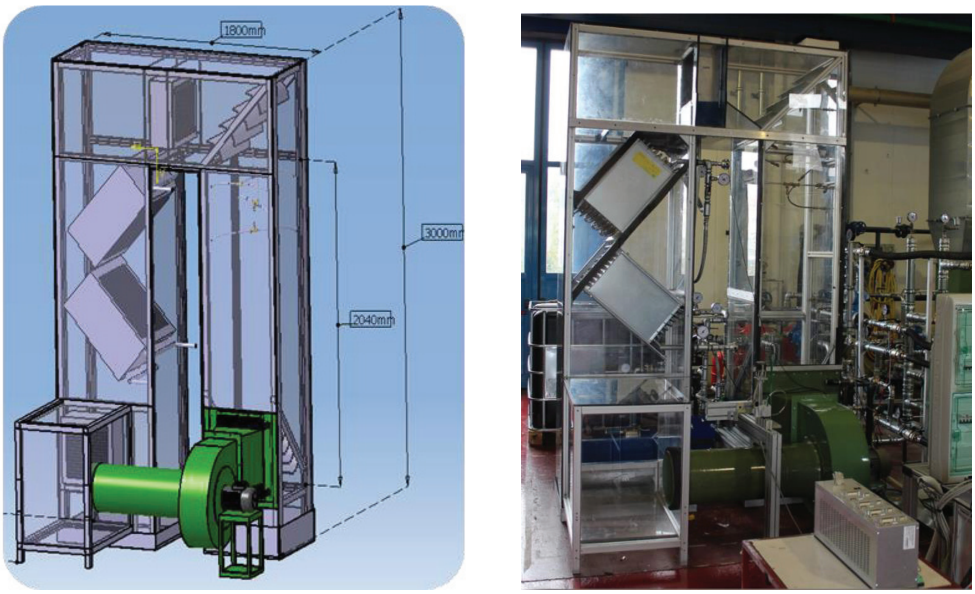


Fig. 2. Virtual image and picture of the HD seawater desalter prototype.

Table 1. Instrumentation devices.

Measurement Instruments	Sensors	Full scale (F.S.)	Accuracy
Pressure transducer	Capacitive membrane	250 Pa	± 1.00% F.S.
RTD	Platinum sensor	-50/+250°C	± 0.12% F.S.
Thermohygrometer	Platinum sensor	+20/+120°C	± 0.80% F.S.
	Capacitance hygrometer sensor	RH 100%	± 1.50% F.S.
Flowmeter	Turbine with optical sensor	10 m/s	± 0.50% F.S.

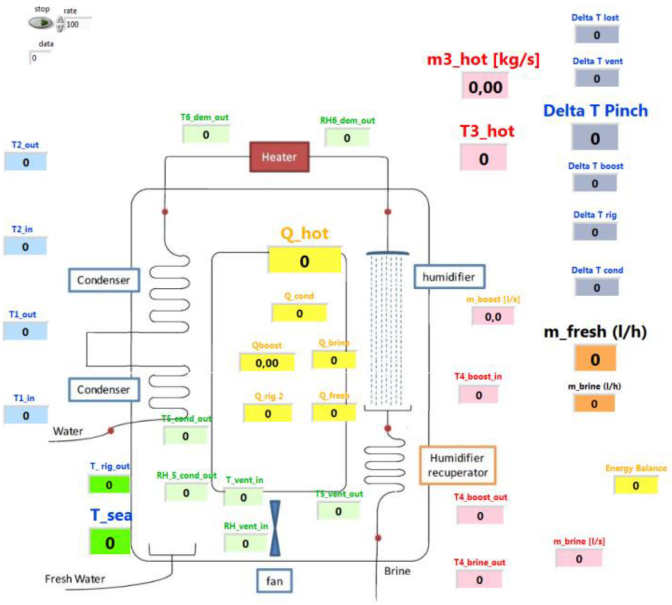


Fig. 3. Front panel of the LabView virtual instrument.

It has to be reminded that for this first experimental investigations water without salt has been used in the seawater circuits, in order to prevent fouling and corrosion issues in the test rig set-up.

Fig. 4. Test bench components: temperature controller, tank, dry air cooler.

Four different configurations have been tested (see Fig. 5). In addition to the base case (CONF1), an HD desalination unit equipped with a recuperative heat exchanger has been experimentally investigated (CONF2): the air-water HX allows to recover heat from the discharged brine and to elevate the air temperature entering the humidification column. The other two configurations have fill media located in the humidification column, respectively without (CONF3) and with (CONF4) recuperative heat exchanger. The goal is to increasing the exchange surface between air and water and to improve the humidification process. The fill pack is composed of a series of corrugated sheets of high quality PVC, which are assembled with the direction of the corrugations inverted every other sheet and glued together to form modules of 1200 mm x 1200 mm x 600 mm. Three fill packs have been located in the humidifier: Figure 6 shows one of them.

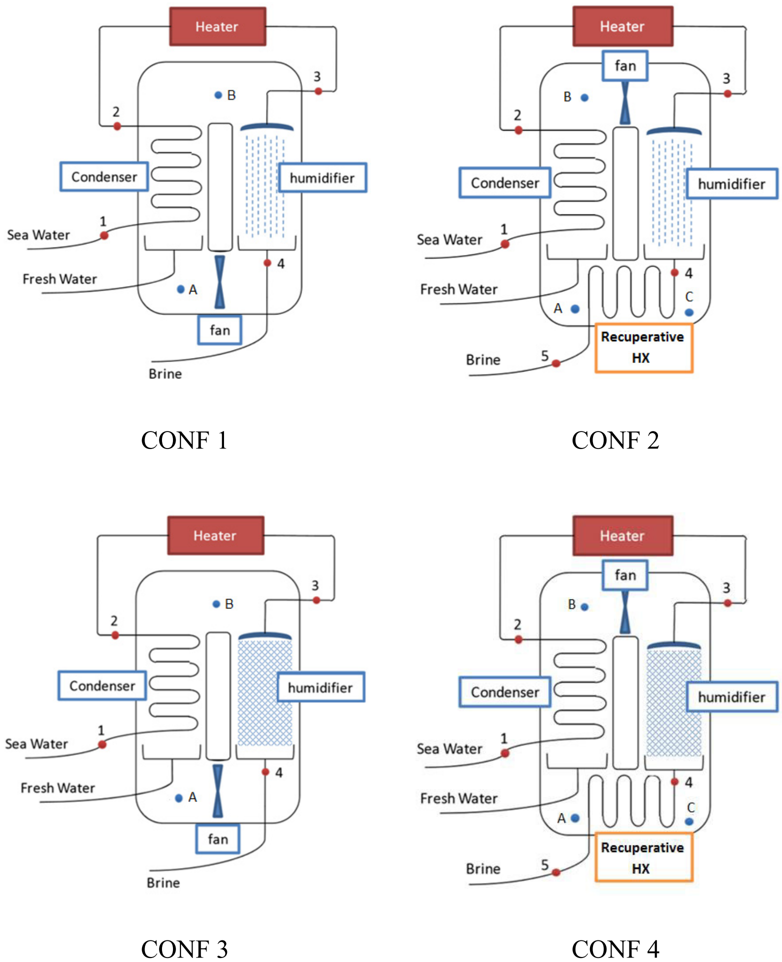


Fig. 5. HD system configurations.

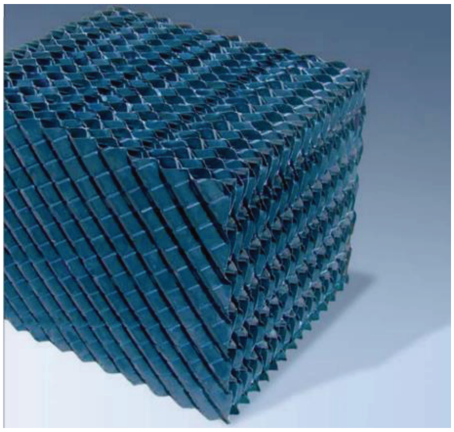
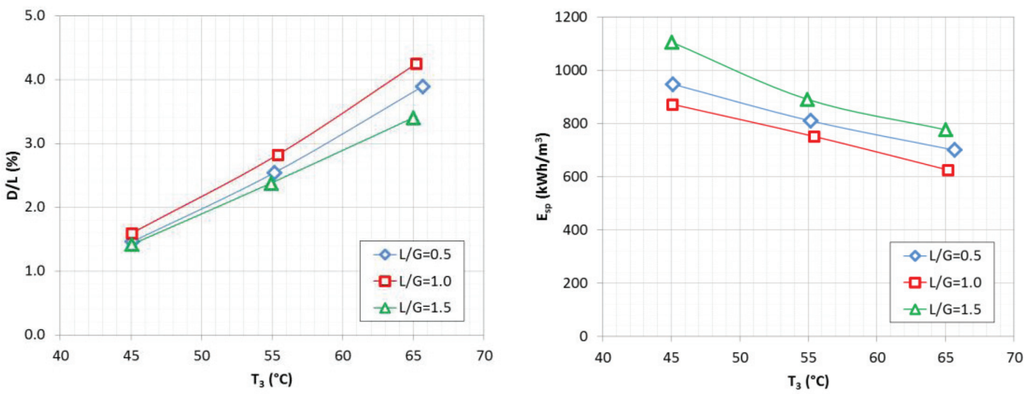


Fig. 6. Fill pack.

4. Experimental results

Firstly, experimental results related to the base configuration (CONF1) are presented and discussed. Refer to Figure 5 for measuring points (1 to 5 for seawater, A to C for air flow). The HD desalination unit has been tested for 9 different operating conditions: seawater temperature and flow rate were set at 23°C (T_1) and 0.135 kg/s (L) respectively, whilst seawater temperature at humidifier inlet (T_3) was varied in the range 45-65°C and the flow rate ratio L/G in the range 0.5-1.5.

Data recording started after an initial transitory period of about 20 minutes, when stationary conditions were established. Figure 7a shows the productivity (D/L) of the base configuration. It can be seen that the higher is the water temperature entering the humidifier, the higher is the freshwater production: this is due to the bigger amount of moisture that warmer air can hold. Looking at the L/G effect, an optimum can be observed, corresponding at L/G = 1.0, in accordance with previous numerical investigations [6]. Figure 7b reports the specific energy consumption related to CONF1 for the investigated operating conditions. This parameter indicates the required heat input per fresh water unit mass ($E_{sp} = Q_{heat}/D$). An increase in the seawater temperature entering the humidifier allows to improve the system efficiency and the best performance takes place for L/G = 1.0. Tab. 2 summarizes air and seawater conditions in all measuring points for the case L/G = 1.0 and T_3 = 55°C.



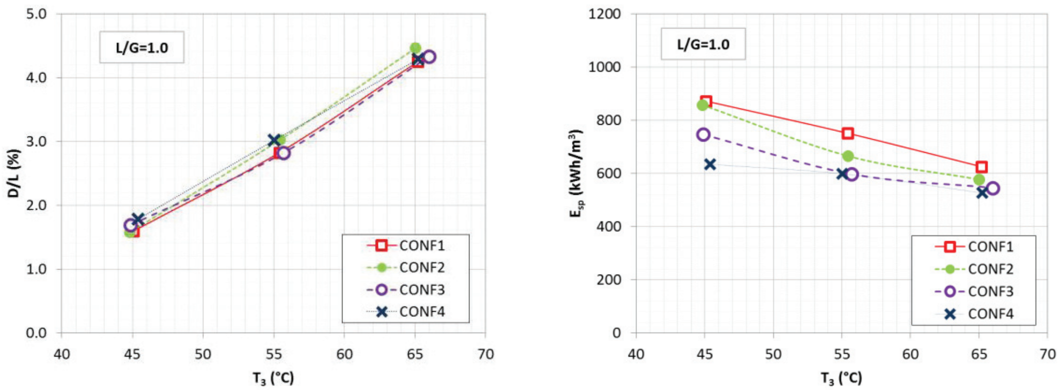
a) b)

Fig. 7. Freshwater productivity (D/L) and specific energy consumption (E_{sp}) for CONF1.

Table 2. Seawater and air properties (CONF1, L/G = 1.0, T_3 = 55°C).

Seawater temperature		Air properties			
T_1	23.0 °C	T_A	26.6 °C	RH_A	100%
T_2	37.7 °C	T_B	40.8 °C	RH_B	100%
T_3	55.4 °C				
T_4	36.8 °C				

Measurement campaigns under similar operating conditions were carried out for the other configurations. Only the results for L/G = 1.0 are here reported. Figures 8a and 8b allow to appreciate the benefit of the recuperative heat exchanger and of the fill medium in the humidification section. Looking at the freshwater productivity, no significant improvements occur: freshwater production ranges from 1.8% at T_3 = 45°C up to 4.5% at T_3 = 65°C for all the cases. This is likely due to a saturation effect in the condensation section, that probably requires more heat transfer surface and currently acts as a bottleneck. On the opposite, a more relevant effect can be observed in the specific energy trend. The recuperative heat exchanger (CONF2 vs. CONF1) allows to save on average about 10% of thermal input. A bigger effect is achieved when the fill packs are located within the humidification column (CONF3 vs. CONF1): in this case, an efficiency increase of about 20% takes place for all operating conditions, thanks to a larger water-to-air contact surface. The combined use of recuperative HX and fill media (CONF4) produces only a marginal efficiency improvement, mainly at low inlet temperatures.



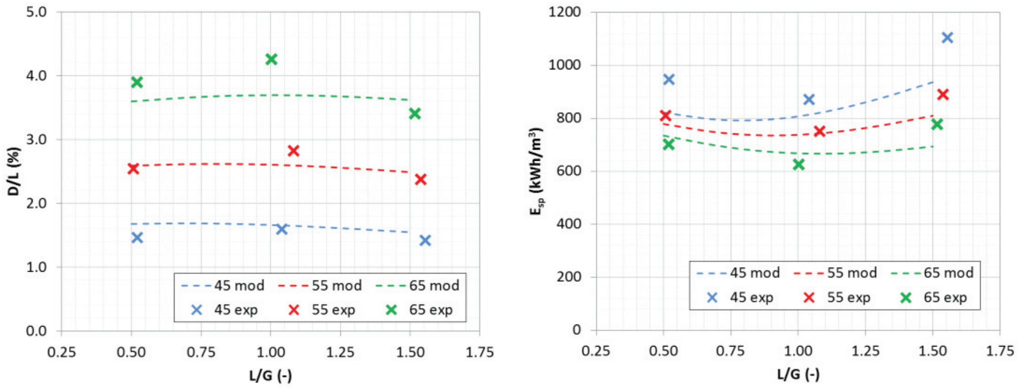
a) b)

Fig. 8. Freshwater productivity (D/L) and specific energy consumption (E_{sp}) for L/G = 1.0 and T_3 = 55°C (all configurations).

5. System modeling

An in-house computer code has been developed to simulate the HD desalination unit and to predict the system behavior. The aim was to have a tool for evaluating the effect of design modifications on the global performance. The model is an evolution of a previous code presented in [6]. Performance maps of the heat exchangers (condenser and recuperative HX) and the 'tower characteristic' kaV/L related to the humidification section were derived from experimental data.

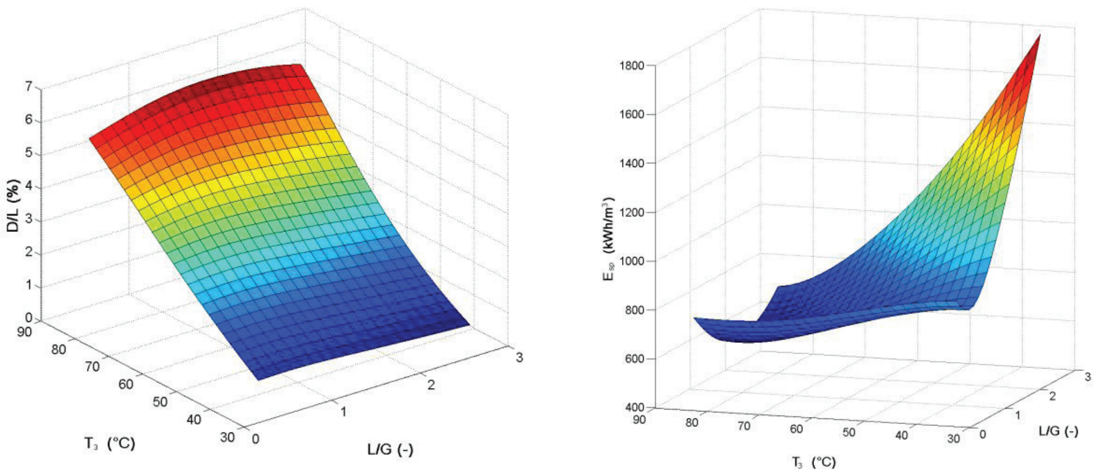
Figure 9 shows a comparison between model predictions (dashed lines) and experimental results related to CONF1. In spite of a slight underprediction occurring at the highest temperature for D/L (*-13%* at L/G = 1.0, see Fig. 9a) and at the lowest temperature for E_{sp} (*-13%* at L/G = 0.5, see Fig. 9b), a general good agreement can be observed both for productivity and specific energy values.



a) b)

Fig. 9. Software prediction vs. experimental results (CONF1).

The computer code was used to estimate the HD desalination system performance for a wider range of flow rate ratios and input temperatures, in order to have a deeper comprehension of the HD desalination behavior under different operating conditions. *L/G* and T_3 were varied in the range 0.35-2.75 and 35-85°C, respectively: Figure 10 presents the performance predictions.



a) b)

Fig. 10. Computed HD unit performance maps.

Figure 10a confirms that an increase in the water temperature at the humidifier inlet is always beneficial for the freshwater production. Looking at the flow rate ratio, its effect appears weaker; nevertheless an optimal value around 1.0 (at low temperature) and around 1.5 (at higher temperature) can be noted. The specific energy curve exhibits an interesting behavior: thermal input at very low temperature is detrimental, and this is particularly true at high *L/G* ratios. The system efficiency significantly increases (and E_{sp} goes down) when seawater is heated at high temperature. In the E_{sp} chart it is clear the presence of an optimal value of *L/G* and this optimum raises when water temperature increases.

6. Conclusions

A prototype of a HD desalination system has been designed and assembled at Bergamo University Labs. The unit was fully instrumented and experimentally investigated on a test bench specifically realized for this purpose. Four different configurations have been compared: the effects of a recuperative heat exchanger and of fill media within the humidification column have been evaluated. This work reports the first results of the planned measurement campaign. It was proved that the system is working properly and it is of potential to be used as a desalination unit of seawater.

A computer code has been developed to accurately simulate the HD desalination unit behavior under different operating conditions. The model predictions have been compared with experimental data and a good agreement has been observed. Then the validated code has been used to predict the HD unit performance for a wide range of water-to-air flow rate ratios and inlet heated water temperature. It has been shown that the system efficiency significantly increases if seawater is heated at higher temperature and an optimal value of *L/G* takes place, whose value varies with the heating source temperature.

Acknowledgements

The authors acknowledge financial support from Regione Lombardia: the present work was funded as part of "RELAB-Renewable heating and cooling Labs" project. A grateful acknowledgment is given to the staff and Master's Degree candidates of Bergamo University who contributed to the work.

References

[1] Picinardi A. Cogeneration of cooling energy and fresh water. PhD Thesis in Energy and Environmental Technologies; University of Bergamo; 2011.
[2] Darwish MA, Al-Najem NM, Lior N. Towards sustainable seawater desalting in the Gulf area. Desalination 2009; 235: p. 58-87.
[3] Nawayseh NK, Farid MM, Omar AA, Al Hallaj SM, Tamimi AR. A simulation study to improve the performance of a solar humidification–dehumidification desalination unit constructed in Jordan. Desalination 1997; 109: p. 277–284.
[4] Xiong R, Wang S, Wang Z. A mathematical model for a thermally coupled humidification–dehumidification desalination process. Desalination 2006; 196: p. 177–187.
[5] Franchini G, Perdichizzi A. Modelling of a solar driven HD (Humidification-Dehumidification) desalination system. Energy Procedia 2014; 45: p. 588-597.
[6] Franchini G, Perdichizzi A. Fresh water and cooling cogeneration by solar energy. ISES Solar World Congress 2009, Johannesburg, South Africa, October 11-14; ISBN: 978-1-920017-42-2.
[7] Al‐Hallaj S, Arid MM, Tamirni AR. Solar desalination with a humidification-dehumidification cycle: performance of the unit. Desalination 1998; 120: p. 273‐280.
[8] Chafik E. A new seawater desalination process using solar energy. Desalination 2002; 153: p. 25‐37.
[9] Bourouni K, Martin R, Tadrist L, Tadrist H. Experimental investigation of evaporation performances of a desalination prototype using the aeroevapo‐ condensation process. Desalination 1997; 114: p. 111–128.
[10] Dai YJ, Zhang HF. Experimental investigation of a solar desalination unit with humidification– dehumidification. Desalination 2000; 130: p. 169–175.
[11] Ben Bacha A. Dynamic modeling and experimental validation of a water desalination prototype by solar energy using humidification dehumidification process. Desalination 2013; 322: p. 182-208.
[12] Yamali C,Solmus I. A solar desalination system using humidification–dehumidification process: experimental study and comparison with theoretical results. Desalination 2008; 220: p. 538-552.