EXPERIMENTAL STUDY OF WATER DESALINATION BASED ON HUMIDIFICATION-DEHUMIDIFICATION PROCESS VIA HEAT PUMP

A. E. Tourab[1], Mohamed A. Teamah[2], Ahmed A. Hanafy[1], Wael M. EL-Maghlany[2]
[1]Arab Academy for Science and Technology and Maritime Transport, Egypt
[2]Faculty of Engineering, Alexandria University, Egypt
Corresponding Author: A. E. Tourab

Abstract

In this paper an experimental investigation was performed on water desalination system using Humidification-Dehumidification process utilizing open air open water (OAOW) air heated heat pump cycle. The effect of the heat pump two coils of the heat pump cycle (the condenser as hot zone and evaporator as a cold zone). Consequently, the coefficient of performance of the cycle is maximized. Air is heated through the condenser and so its ability to absorb water is increased. Via water nozzles, water at normal temperature is sprayed in the hot air. Three different techniques including cross, counter and parallel spraying flows have been applied. Through the evaporator, the distilled water is condensed from the moist air at exit from the sprayers. The effect of the top temperature on the amount of condensate was studied. Results of the experiments showed that the parallel flow had the highest productivity.

Keywords: Desalination, Humidification-Dehumidification, Heat pump

Corresponding Author: A. E. Tourab

1. INTRODUCTION

Water represents the lifeblood for all living creatures. It is the basic element in agriculture growth and industrial prosperity, in addition to providing pure water for mankind purposes. Water on earth represents approximately 70% of earth's surface area where $1.4 \times (10)^9\ km^3$ of water covers this area; salt water represents the great divide on earth by a percentage of 97.5%, while the fresh water by 2.5% with 80% of this amount is iced in the icecaps or underground water. This makes it difficult to attainable for human use, so 0.5% of fresh water is supported for all human life [1]. The world population is about 7 billion people and it's predicted to be doubled in the next 50 to 90 years and the amount of fresh water resources still constant. In 2003 above 400 million people around the world suffers water shortage, this statistics was estimated to increase to 2.8 billion people by 2050 [2]. Farrag et al. [3] performed experiments for two stage water desalination by HDH process closed air using saline water heated by evacuated tube solar water heater. The maximum flow rate was 18.5 L/h at inlet water temperature of 80℃ with condensation efficiency of 24.6%, the energy consumption was 12.8 kWh/m^3, and also it was found that the enhancement in the rate of evaporation in the humidification process was by decreasing the water drop diameter with GOR of 4.2. Zamen et al. [4] carried out an experimental investigation of a multi-stage solar HDH desalination process. It was found that the production of fresh water in summer is more than twice the production in winter. Kabeel et al. [5, 6] performed a numerical and experimental investigation to a hybrid solar desalination system of air HDH and water single stage flashing evaporation, they discerned that the HDH unit and single stage flashing evaporation unit productivity affected by the heat recovery in using mixing tank, but the saline feed water, wind speed and ambient temperature have the least effect on the productivity of fresh water. El-Minshawy et al. [7] carried out an experimental study on productivity augmentation of a novel solar HDH system using water heaters, induced atmospheric air and external reflector, the maximum efficiency of the system was 77% which increased as solar radiation increased. Yuan et al. [8] preceded an experiment on solar HDH system to generate fresh water; it was found that, the productivity of fresh water increased as solar radiation increased. Yanniotis et al. [9] studied two types of air humidifiers, namely pad and tubular spray humidifiers. The experimental results showed that the evaporation rate for both seawater and tap water were comparatively the same. El-Shazly et al. [10] improved the performance of HDH desalination unit using a pulsating water flow, the results showed that the productivity increased by increasing the off time through decreasing the frequency of pulsated water. It was found that by increasing the water flow per pulse the productivity increased. Mehrgoo and Amidpour [11] studied the performance optimization of direct contact HDH unit with three main sections, humidifier, dehumidifier and heating source. The results showed that, the highest production rates were obtained at high air flow rate and low hot water flow rate.

2. Experimental test rig and procedures

2.1. Experimental test rig description

The OAOW air heated HDH unit was integrated with a vapor compression unit. The cycle based on the operating principal of a vapor compression cycle. Figure (1) shows a schematic diagram of the test rig. The unit consists of four main sections; in section 1, the air was drawn by a blower through two adjustable gates passing through air filters to remove any dust or impurities. The blower was utilized in 753×750×700 mm duct in couple with 1 m flexible duct of 10 inches diameter to section 2.

In section 2, air passes through the condenser that was utilized in 530×500×400 mm. As a result, the air dry-bulb temperature increased sensibly with progress decreasing in the relative humidity made the air to be gluttonous to water. In section 3, the air is passed through a duct of 1500×500×400 mm. Through this section, the air was adiabatically humidified via air washer. The humidifier was employed with 0.5 HP water pump and very fine swirl atomizers consists of 4 holes of 0.5 mm diameter each. The humidification has been achieved in cross, counter and parallel flow according to the direction of both air and water. At the exit of the humidifier, the humidified air was passed through a duct of 530×500×400 mm in section 4 that was included the evaporator. In this section, fresh distilled water was accumulated as productivity.

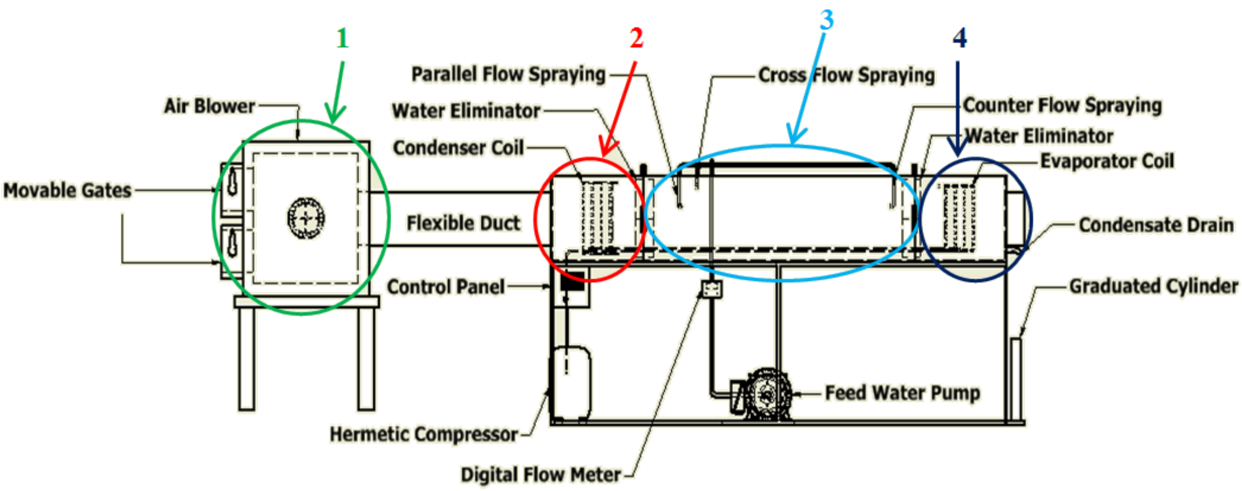

Fig 1: Schematic diagram for the test rig.

2.2. Experiment procedure

The following procedures have been carried out for executing the experiments:

- Humidity and temperature monitor program was switched on and starts to record data from sensors and the data logger turned on.
- Fan gates were adjusted to the specified position that results in a specified air velocity measured by telescopic van-anemometer and hot wire anemometer and the fan was turned on.
- The heat pump of a 3 HP compressor was turned on.

- Water sprayer adjusted to a specified way in spraying (cross, counter and parallel) and the water pump switched on.
- Monitoring the readings of temperature and relative humidity until reaches the steady state in 20 to 30 minute.
- When steady state condition achieved:
    - Start countdown timer in 15 minute.
    - Accumulate the fresh water at the starting of the counter time in a graduated cylinder.
    - Measure and record the amperage consumed by fan, pump and compressor.
    - Measure and record the flow rate of sprayed water.
- When the 15 minutes ends up, the heat pump, air blower and water pump switched off.
- Wait until the bleeding of fresh water stopped.
- Record the amount of fresh water accumulated in the graduated cylinder.

3. Error Analysis

Taking in consideration errors came from the measuring instruments which affects the accuracy of measurements during the experiments as it shown in Table (1). The maximum error of all measuring instruments can be defined as it's the ratio between its accuracy to the maximum value measured by this instrument. Accuracy and ranges of each measuring instrument are shown in Table (1) as it obtained from measuring instrument specification data sheet.

Table 1: Experimental measuring instruments with accuracy, range and error

Measuring instrument	Accuracy	Range	Error (%)
Telescopic van-anemometer	±0.2 m/s	0.6 to 40 m/s	4.50
Hanna Instruments HI9564 Thermo-hygrometer	3 % RH	20 → 95 % RH	0.075
	±0.5 °C	0 → 60 °C	2
Electronic turbine Digital flow meter	±1.0% lpm	6 → 120 lpm	45.4
Digital Temperature & Humidity Sensor Module (DHT22)	2-5% accuracy (Humidity)	0-100%	0.125
	±0.5°C accuracy (Temperature)	-40 to 80°C	2.6
Water proof temperature sensor	±0.5°C	-55 to 125°C	5
Digital clamp ampere	1.5% amp	0 to 200 amp	1.5
E-Type Thermocouple	±1.7°C	-270 to 870°C	21.25

4. Mathematical analysis and data reduction

The dry bulb temperature and relative humidity were measured before and after each element to get the properties of air. These measured data were needed in calculating, the amount of humidity in air after the humidifier, the amount of condensate fresh water, the effectiveness of the condenser, the humidifier, and the evaporator.

The amount of humidity in air could be estimated from:

$$\omega_{spraying} = \omega_3 - \omega_{out} \tag{1}$$

The amount of condensate can be calculated from:

$$\dot{m}_{condansate} = \dot{m}_{air} \times (\omega_{spraying}) \tag{2}$$

The effectiveness of the coils can be calculated as:

$$\varepsilon = \frac{\dot{Q}_{actual}}{\dot{Q}_{max}} \tag{3}$$

The humidification effectiveness of the humidifier sector can be calculated as:

$$\varepsilon_h = \frac{\omega_3 - \omega_2}{\omega_{saturation} - \omega_2} \tag{4}$$

The dehumidification effectiveness of the dehumidifier sector can be calculated from:

$$\varepsilon_{deh} = \frac{\omega_3 - \omega_4}{\omega_1 - \omega_3} \tag{5}$$

5. Experimental Results and Discussion

For an OAOW air heated HDH desalination system, many parameters have been studied in this experimental works. The experimental measured data have been collected after reaching steady state condition which was ranged between 20 to 30 minutes. For a constant maximum sprayed water flow rate of 2.2 L/min, the quantity of the air flow was changed and the effect of the water to air mass ratio effect has been investigated on the cycle performance and the amount of output condensate. Also, the effect of sprayed water flow direction on the system performance has been studied.

In Fig. 3, the results indicated that the parallel flow has the highest freshwater productivity up to 2.34 L/h, while counter flow came in the second position with a maximum productivity up to 2.12 L/h, finally, the cross flow with a maximum productivity of 1.36 L/h. In general, the increase in the water to air mass ratio led to the increase in the productivity rate. But, in parallel flow, the progressing in the productivity rate was sharp. This due to air flow direction was in the same direction of the sprayed water, which led to good mixing in the humidifier sector and consequently led to efficient heat and mass transfer in compared to cross and counter flows. It is denoted that in the cross flow; the water to air mass ratio effect on the productivity is minor. This is due to the small contact area between water and air in the humidifier sector.

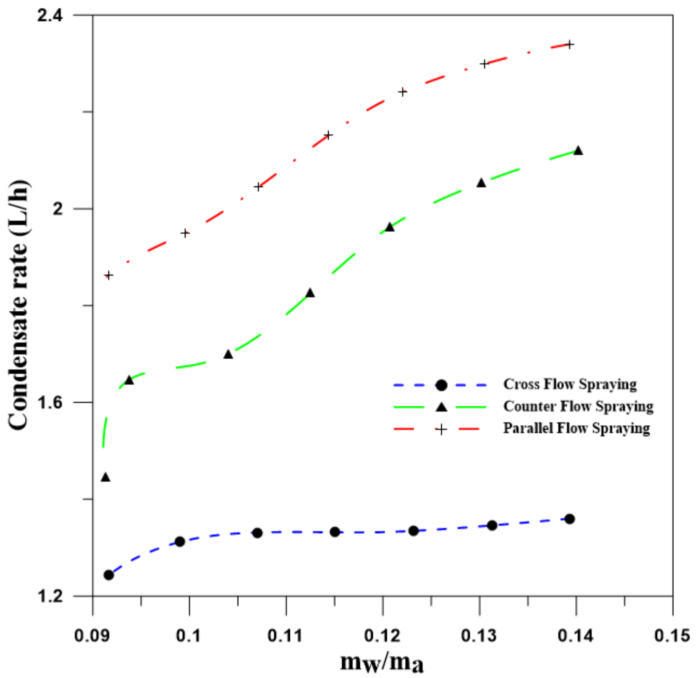

Fig 3: Amount of condensate for the 3 types of water spray flow against water to air mass ratios.

The humidifier effectiveness has great effect on the production of fresh water where it indicates the percentage of humidification process as it increases the condensate rate increases. Showing in Fig. 4, the humidifier effectiveness across the three flows spraying systems (cross, counter and parallel), it showed that parallel flow spraying of the highest effectiveness followed by counter and cross flows spraying respectively, which illustrates why parallel flow spraying have the highest productivity. Also it was noticed that as water to air mass ratio increases humidifier effectiveness increases.

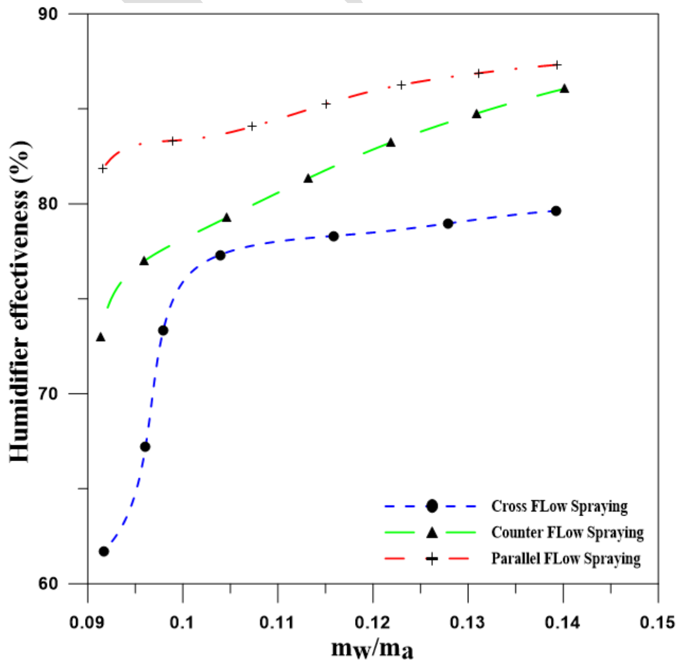

Fig 4: Humidifier effectiveness at different mass ratios.

The productivity of the unit do not depends only on how much water content could be held by air flow but also depends on the extraction process of this water content (dehumidification process). In Fig. 5, dehumidifier effectiveness in parallel flow spraying has the highest values and as water to air mass ratio increases the effectiveness increases. This indicates that as the dehumidifier effectiveness increases the condensate rate increases confirming on the results showed in Fig. 3.

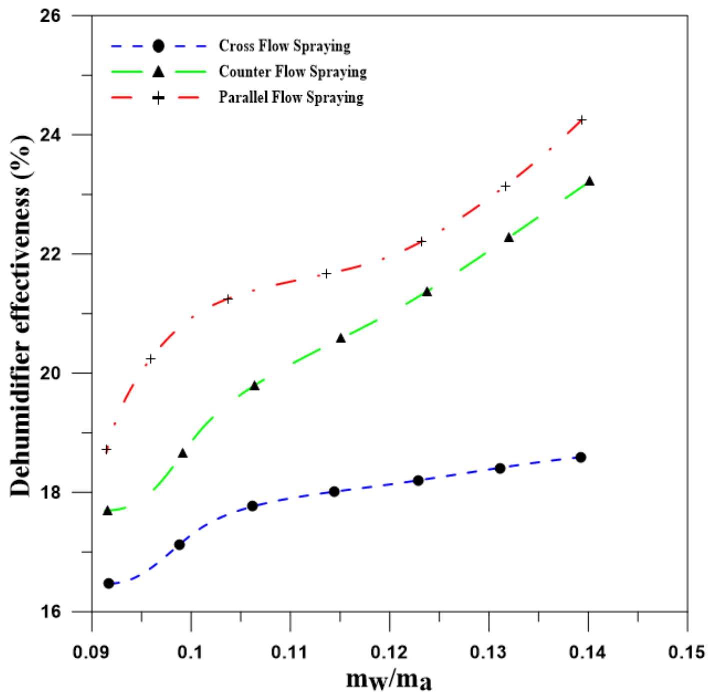

Fig 5: Dehumidifier effectiveness at different mass ratios.

In Fig. 6, an important parameter that is affecting productivity of fresh water which is the air top temperature. It's the temperature of air heated by the condenser of a heat pump cycle and considered the highest temperature in the HDH cycle. It was noticed that as the air top temperature increases the amount of condensate increases and vice versa.

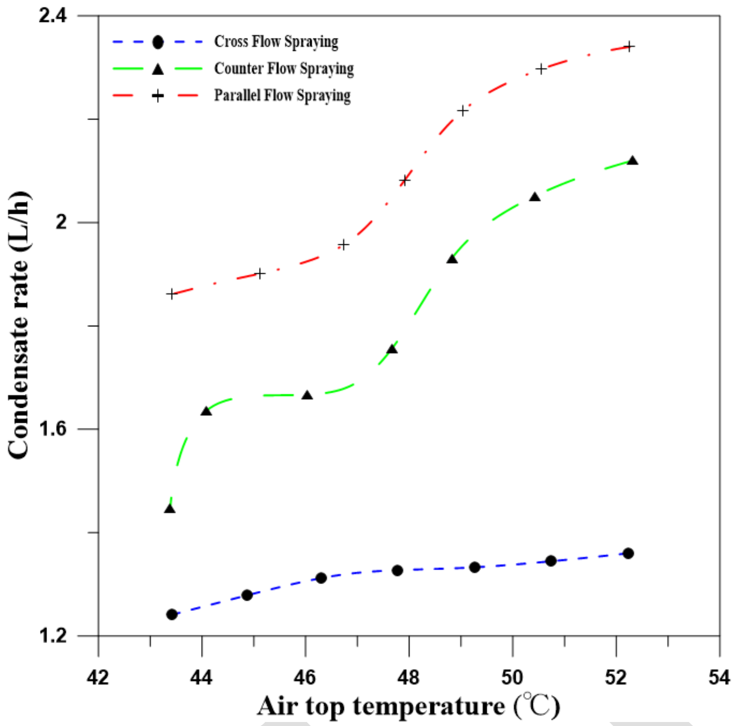

Fig 6: Effect of top temperature on condensate rate on different water flow sprays directions.

6. CONCLUSIONS

In this paper it was investigated experimentally a water desalination system based on HDH process using heat pump. Water needed to be desalinated has been sprayed in 3 directions (Cross, Counter and Parallel flows) according to the flow of air. It was concluded the following from the experiments:

- The parallel flow of the sprayed water has the maximum productivity to reach 2.34 L/h.
- The humidifier effectiveness has the highest values in the parallel flow of 87.31%.
- The amount of condensate affected by water to air mass ratio as it increases the productivity increases.
- The top temperature affects directly the amount of condensate, when the top temperature increases air becomes more gluttonous to water, consequently air will carry more water in a form of vapor.

REFERENCES

[1]. Hisham T. El-Dessouky and Hisham M. Ettouney, Introduction, *Fundamentals of Salt Water Desalination*, Elsevier Science, Netherlands, 2002.

[2]. https://www.census.gov/population/international/data/idb/worldpopgraph.php.

[3]. Taha E. Farrag, Mohamed S. Mahmoud and Wael Abdelmoez, Experimental Validation for Two Stages Humidification-Dehumidification (HDH) Water Desalination Unit, Seventeenth International Water Technology Conference, Istanbul, Turkey, IWTC 17 2013.

[4]. M. Zamen, S.M. Soufari, S. Abbasian Vahdat, M. Amidpour, M.A. Zeinali, H. Izanloo, H. Aghababaie, Experimental investigation of a two-stage solar humidification–dehumidification desalination process, Desalination, 332 (2014) 1–6, 2013.

[5]. A. E. Kabeel, Emad M. S. El-Said, A hybrid solar desalination system of air humidification dehumidification and water flashing evaporation Part I. A numerical investigation, Sixteen International Water Technology Conference, Istanbul, Turkey, IWTC16 2012.

[6]. A.E. Kabeel, Emad M.S. El-Said, A hybrid solar desalination system of air humidification, dehumidification and water flashing evaporation: Part II. Experimental investigation, Desalination, 341 (2014) 50–60, 2014.

[7]. Nabil A.S. Elminshawy, Farooq R. Siddiqui, Mohammad F. Addas, Experimental and analytical study on productivity augmentation of a novel solar humidification–dehumidification (HDH) system, Desalination, 365 (2015) 36–45, 2015.

[8]. Guofeng Yuan, Zhifeng Wang, Hongyong Li, Xing Li, Experimental study of a solar desalination system based on humidification–dehumidification process, Desalination, 277 (2011) 92–98, 2011.

[9]. S. Yanniotis, K. Xerodemas, Air humidification for seawater desalination, the European Conference on Desalination and the Environment: Fresh Water for All, Malta, 4-8 May, 2003.

[10]. A.H. El-Shazly, A.A. Al-Zahrani, Y.A. Alhamed, S.A. Nosier, Productivity intensification of humidification–dehumidification desalination unit by using pulsed water flow regime, Desalination, 293 (2012) 53–60, 2012.

[11]. Morteza Mehrgoo, Majid Amidpour, Constructal design and optimization of a direct contact humidification–dehumidification desalination unit, Desalination, 293 (2012) 69–77, 2012.