ENHANCEMENT OF WATER DESALINATION BY USING HUMIDIFICATION AND DEHUMIDIFICATION PROCESSES

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Abstract. *Experimental and theoretical work investigates the principal operating parameters of a proposed desalination process working with an air humidification-dehumidification method. The main objective of this work was to determine the humid air behavior through single-stage of desalination system. The experimental work studied the influence of the operating conditions such as the water temperature, the saline water level and the air flow rate to evaporator chamber on the desalination performance. The experimental results show that, the productivity of the system increases with the increase of the water temperature and the decrease of the airflow rate. The productivity of the system is moderately affected by the water temperature and airflow rate and slightly affected by the water level. The efficiency of the desalination system is higher for* M_a*=12.6 and* M_a*=14 kg/hr at different water levels. At 80 °C, the productivity of the system is higher at different water levels and airflow rate. Within the studied ranges, the maximum productivity of the system reached to 0.81* kg_w/kg_a *at 87 °C for water and* M_a*=4.2 and* M_a*=8.4 kg/hr. A good agreement had been achieved with productivity calculations.*

Keywords: *Air humidification and dehumidification process, Desalination system*

1. Introduction:

Water desalination by humidification and dehumidification has been the subject of many investigations. Different experimental data are available for using HDD at the pilot or industrial scale. An inspection of these data allows establishing many perspectives for this process. Previous literature studies focused on performance evaluation of the HDD system combined with solar energy , Farid and Al-Hajaj (1996), Farid et al (2002), Nafey et al (2004, 2004) and Nawayseh et al (1999). Dai and Zhang (2000) utilized structured packing in the humidification unit. The unit was 1 ×1×1.5 m in dimension. They replaced the collector by a boiler to provide the hot water, which was sprayed at the surface of honeycomb packing of the humidifier. A fan was used to force the process air to flow through the humidifier in a cross flow arrangement. The results show that, the thermal efficiency and water production increases with increase of mass flow rate of water to the humidifier. The thermal efficiency and water production increase significantly with temperature of inlet water into humidifier. An efficiency of 80% was obtained using hot water feed from a boiler. This corresponds to about 68% only when a solar collector is used. Productivity achieved was around 6.2 $kg/m^2/d$.

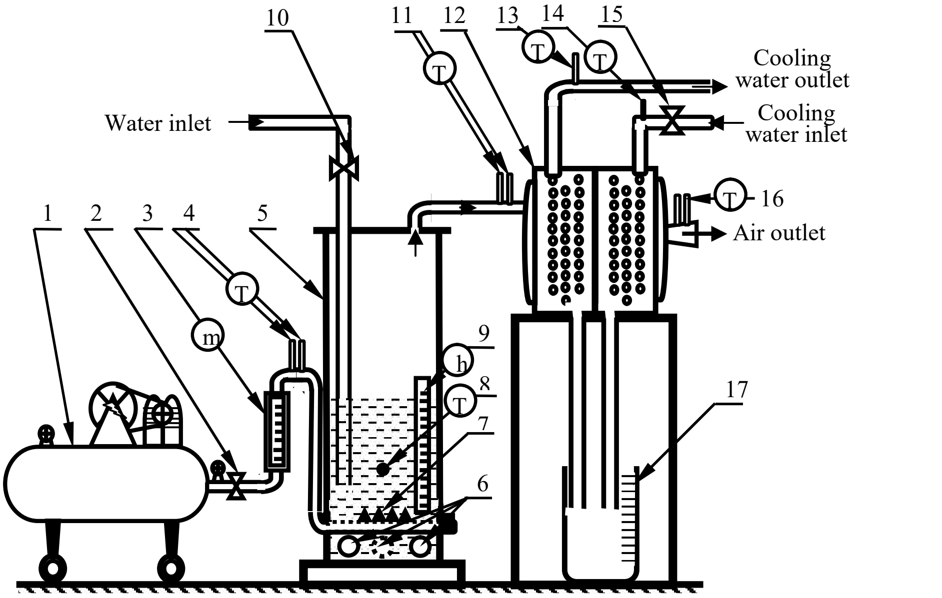
It is also of interest to mention the multiple effect humidification solar desalination technique presented by Ben-Amara et al. (2004), Chefik (2002, 2003), and Ettouney (2005). This technique consists of several steps of air heating and humidification and leads to high vapor concentration in the airflow. Other literature studies of the HDD system includes performance evaluation by Al-Hallaj et al (1998), correlation development for the heat and mass transfer coefficients by Nawayseh et al (1999) or mathematical modeling by Nawayseh et al (1999), Orfi et al. (2007), Xiong et al. (2006), Younis et al. (1993), Yuan and Zhang (2007). Yamali and Solmus (2007) investigated theoretically the effect of different system operating conditions, types of air heater, and some different design parameters and a weather condition on a solar water desalination system performance under the climatologically conditions. The system productivity is increased up to 8% by using a double-pass solar air heater compared to a single pass solar air heater and decreased about 30% without double-pass solar air heater under the same operating conditions.

El-Agouz and Abugderah (2008) presented an experimental investigation of humidification process by air passing through saline water. The study presented the behavior of humid air through single-stage of heating-humidifying processes. There experimental work studied the influence of the operating conditions such as the water temperature, the headwater difference, the air velocity and the inlet air temperature to evaporator chamber on the vapor content difference and humidification efficiency. The different air inlet temperatures are studied. The experimental results show that, at 75 °C, the maximum vapor content difference of the air was about 222 gr_w/kg_a. The inlet air temperature to evaporator chamber variation was found to have a small affect on the vapour content difference.

The main objective of this work is to experimentally and theoretically, investigate the principal operating parameters of a desalination process working with an air humidification-dehumidification method. The experimental work studied the influence of the operating conditions such as the water temperature, the saline water level and the airflow rate to evaporator chamber on the desalination system performance.

2. Experimental setup

Figure (1) illustrates a schematic diagram of the experimental setup. The system main components are air compressor (1), evaporator chamber (5) and dehumidifier (12). The desalination system consists of two loops, one for cold saline water and the other for air. In the water loop, the cold saline water for evaporator chamber (5) and dehumidifier (12) is supplied from an external source. The water level in the evaporator chamber is controlled by external graduate level (9) and three electric heaters (6) of 1.2 kW power each heat the water. The water level in evaporator chamber is maintained constant and is regulated by a control valve (10). The cold-water passes through inner tube of the dehumidifier and is regulated by a control valve (15). *In the air loop*, air for the evaporator chamber (5) is taken from the air compressor discharge, is regulated by a control valve (2), and then is passes through flow meter (3). The airflow enters into the evaporator chamber from forty-four holes (7) of 15 mm diameter located at top side of the copper pipe, which is submersed in the water of the evaporator chamber. The air flows through water level in evaporator chamber and carries the evaporated water to dehumidifier (12), where the air is cooled and dehumidified and produced water through a tube to the desalinated water tank (17).



1) air compressor
2) flow control valve
3) air flow meter
4) digital thermometer
5) evaporator chamber
6) electric water heaters
7) forty-four holes
8) thermometer PT-100
9) graduate lever
10) flow control valve
11) flow control valve
12) digital thermometer
13) dehumidifier
14) digital thermometer
15) digital thermometer
16) digital thermometer
17) desalinated water tank

Figure (1). Schematic diagram of the experimental setup.

3. Data acquisition system

For the measurement of the humidity by the dry-bulb/wet-bulb temperature method, resistance thermometers are used because of their high accuracy. The humidity and enthalpy of the air at the different points are calculated by Computer-Aided Thermodynamic. The vapor content difference in evaporator chamber is defined as:

$$\Delta\omega)_{ev} = \omega_{ev})_{out} - \omega_{ev})_{in} \tag{1}$$

where: $\omega_{ev})_{in}$, $\omega_{ev})_{out}$ are the inlet and outlet air humidity of the evaporator chamber.
The humidification effectiveness of the evaporator chamber is given by:

$$\eta_{hu} = 100\frac{\omega_{ev})_{out} - \omega_{ev})_{in}}{\omega_{out})_{sat} - \omega_{ev})_{in}} \tag{2}$$

where: $\omega_{out)\ sat}$ is the outlet saturation air humidity of the evaporator chamber
The power input to the evaporator chamber is defined as

$$Q_{in} = m_{air}[h_{air,out} - h_{air,in}] + \Delta\omega)_{ev} C_p [T_{w,ev} - T_{w,in}] \tag{3}$$

where $h_{air,out}$, $h_{air,in}$, $T_{w,ev}$, $T_{w,in}$, $\Delta\omega)_{ev}$ and C_p are the inlet air enthalpy of the evaporator chamber, the outlet air enthalpy of the evaporator chamber, the water temperature in evaporator chamber, the temperature and mass rate of water inlet evaporator chamber as makeup and specific heat of water respectively.

The efficiency of the desalination system is given by:

$$\eta_d = 100\,(\dot{m}\,L_w)_{vap} / Q_{in}) \tag{4}$$

where: $\dot{m}$ is the productivity of system, $L_w)_{vap}$ is the latent heat of vaporization of water

4. Model validation

The present experimental results are verified by comparing the obtained results with other published experimental results by Dai and Zhang (2000) and Garg et al. (2002). Fig. (2) shows good agreement between Dai and Zhang (2000) and Garg et al. (2002) results and the present results under the same operating water temperature. The present results show that the productivity is approximately 0.27 kg_w/kg_a at 70 °C and 0.75 g_w/kg_a at 85 °C. The results showed that productivity is approximately 0.1745 kg_w/kg_a at 85 °C by Dai and Zhang (2000), and the productivity is approximately 0.066 kg_w/kg_a at 70 °C by Garg et al. (2002). Thus, the productivity for the present is increased around 4.3 and 4.1 times than Dai and Zhang (2000) and Garg et al. (2002) results. In addition, El-Agouz and Abugderah (2008) presented more details for this model.

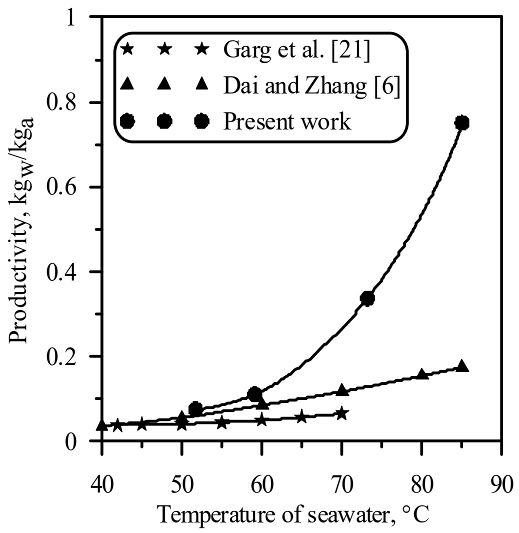


Figure (2). System validation.

5. Results and discussion

The effect of water temperature and level increase in the evaporator chamber on the productivity of the system is shown in Fig. (3). It is evident from the figures at constant airflow rate that as the temperature and level of the water increase, the productivity is increased. On the other hand, the productivity is slightly affected by the inlet airflow rate and water level at low water temperatures less than 70 °C and the productivity is increased at water temperatures higher than 70 °C.

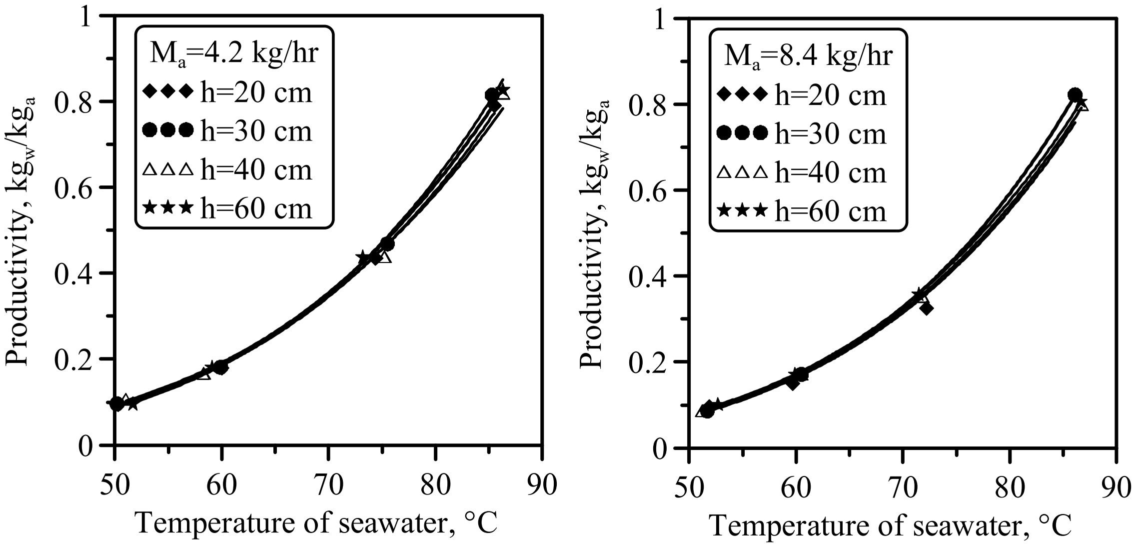


Figure (3). Effect of the temperatures of saline water on productivity

In addition, as the inlet airflow rate increases, the productivity is decreased. This increase in the system output is due to the decrease of the difference between the air dry-bulb/ wet-bulb temperatures.

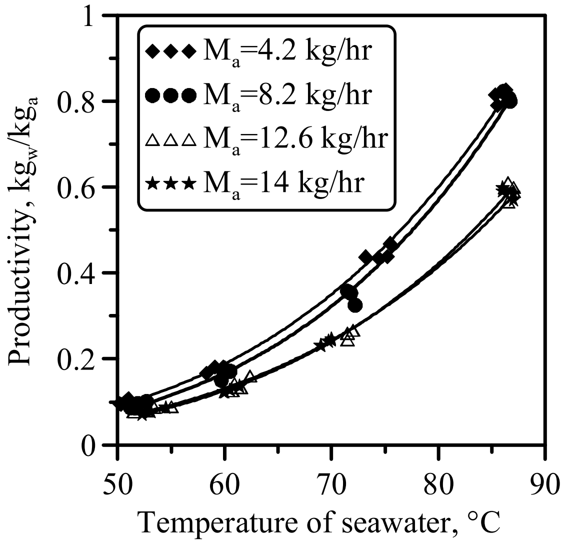


Figure (4) Effect of the temperatures of saline water on productivity at different air flow rate

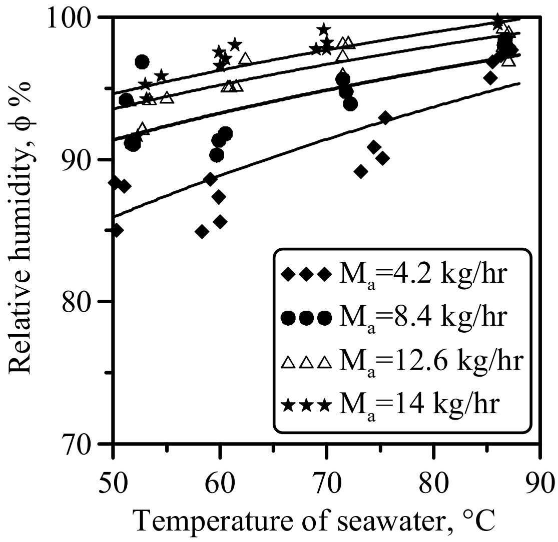


Figure (5) Effect of the temperatures of saline water on relative humidity at different air flow rates

The effect of water temperature and airflow rate increase in the evaporator chamber on the productivity of the system is shown in Fig. (4). It is clear from the figure that as the water temperature increases, the average productivity is increased. As the temperature of the saline water in evaporator chamber is increased from 55 °C to 85 °C, the increase of average productivity of the system is 540% and 440%. The effect of water temperature and airflow rate increase in the evaporator chamber on the relative humidity of the system is shown in Fig. (5).

It is clear from the figure that as the water temperature increases, the average relative humidity is increased. On the other hand, the average relative humidity increased with the increase of airflow rate. Since the productivity is slightly affected by the increase of water level in evaporator chamber. Therefore, the average productivity , $\dot{M}_w)_{av}$, of the system for different air flow rate can be correlated as a function of the temperatures of saline water with maximum deviation 3% as follows:

$$\dot{M}_w)_{av} = A \; T_w^{\,B} \qquad kg_w / kg_a \tag{5}$$

Table (1) show constants (A, B) of Eq.(5).

M_a, kg/hr	A	B
4.2	1.967E-10	4.96
8.4	1.95E-10	4.95
12.6	8.187E-9	4.04
14	4.444E-9	4.19

Figure (6) shows the relationship between the humidification effectiveness and the temperatures of water at different airflow rate and water level. From the figures, the humidification effectiveness increases with the increase of water temperature and airflow rate at different water level. The humidification effectiveness is higher for Ma=14 kg/h at different water level.

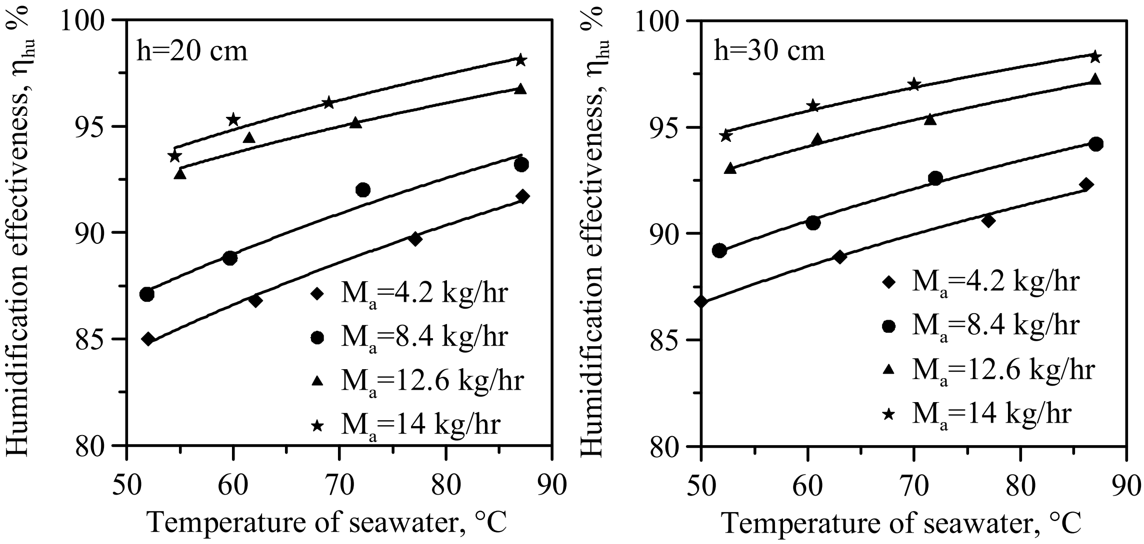


Figure (6). Effect of the water temperature on the humidification effectiveness.

Effect of water level and airflow rate increase in the in evaporator chamber on the productivity of the system at Tw=50, 60, 70 and 80 °C is shown in Fig. 7. It is evident from the figure that as the level of the water increases, the productivity is increased at all water temperature. On the other hand, as the airflow rate increases, the productivity is increased at Tw= 60, 70 and 80 °C except for Tw= 50 °C is decreased.

At Tw=50 °C, as the water level in evaporator chamber is increased from 20 to 60 cm, the increase in productivity of the system is 7.75%, 11.41%, and 2.95 % at airflow rate 4.2, 8.4 and 14 kg/hr. In addition, at

water level 60 cm, the increase of airflow rate from 4.2 to 8.4 kg/hr resulted in an decrease of 1.81 % in the productivity and it is increased from 4.2 to 14 kg/hr resulted in an increase of 8.15 % in the productivity.

At Tw=60 °C, as the water level in evaporator chamber is increased from 20 to 60 cm, the increase in productivity of the system is 7.42%, 5.55%, and 4.39 % at airflow rate 4.2, 8.4 and 14 kg/hr. In addition, at water level 60 cm, the increase of airflow rate from 4.2 to 8.4 and from 4.2 to 14 kg/hr resulted in a decrease of 4.7% and 6.67 % in the productivity. At T_w=70 °C, as the water level in evaporator chamber is increased from 20 to 60 cm, the increase in productivity of the system is 10.33%, 10.5%, and 3.8 % at airflow rate 4.2, 8.4 and 14 kg/hr. In addition, at water level 60 cm, the increase of airflow rate from 4.2 to 8.4 and from 4.2 to 14 kg/hr resulted in a decrease of 6.4% and 17.65 % in the productivity. At T_w=80 °C, as the water level in evaporator chamber is increased from 20 to 60 cm, the increase in productivity of the system is 11%, 10%, and 6.24% at airflow rate 4.2, 8.4 and 14 kg/hr. In addition, at water level

60 cm, the increase of airflow rate from 4.2 to 8.4 and from 4.2 to 14 kg/hr resulted in a decrease of 5.8% and 26 % in the productivity.

5.1. The comparison between experimental measured and experimental calculated productivity

Figure (8) shows a comparison between the experimentally measured and calculated productivity. The approximated agreement between the two is good and the average shift between results is about 7.7%, 8.5%, 9.94% and 4.5% at airflow rate 4.2, 8.4, 12.6 and 14 kg/hr. This is due to the change of surrounding conditions, losses in system and error in measurement. The decreases between the experimental productivity measurement and calculation due to the increase of mass of air which increase air velocity and decrease vapor condensations in evaporator chamber.

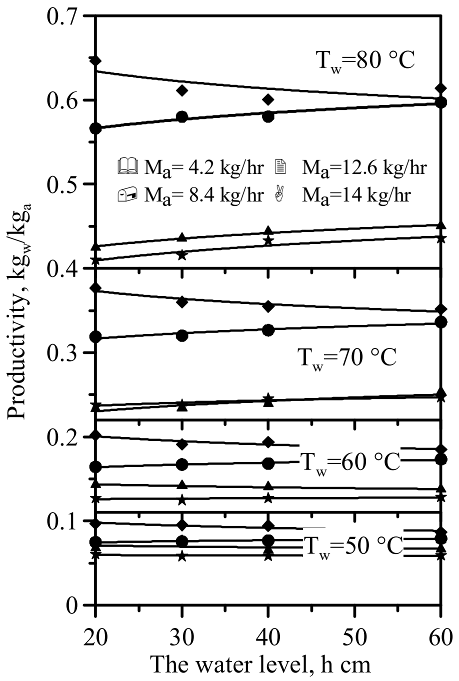


Figure (7). Effect of the saline water lever on productivity for different water temperatures

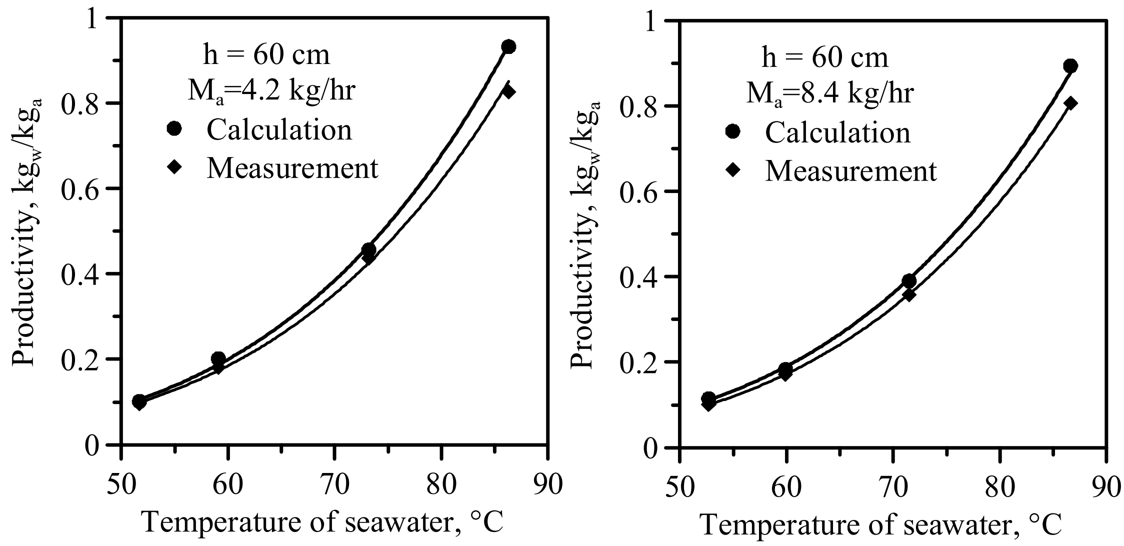


Figure (8). Comparison between the experimentally measured and calculated productivity.

5.2. Present correlations

It is very important to correlate numerical results. If the design equation is general, it will be more useful in engineering applications. The general correlation of productivity of the system as function of water temperature, water level and airflow rate are obtained by use the Microsoft Office Excel Solver tool which, uses the Generalized Reduced Gradient (GRG2) nonlinear optimization code, which was developed by Leon Lasdon, University of Texas at Austin, and Alan Waren, Cleveland State University. The productivity of the system can be correlated with maximum deviation 7% as follows:

$$\dot{M}_w = 1.597 \times 10^{-7}\,(T_w)^{3.971} \times (0.127 + 2352 \times 10^{-7}\,h) \times (0.87231 - 0.02473\,\dot{M}_a) \qquad (6)$$

At: $50 \le T_w \le 87$;
$20 \le h \le 30$;
$4.2 \le \dot{M}_a \le 14$

6. Conclusions

The experimental and theoretical investigation of the principal operating parameters of a desalination process working with an air humidification-dehumidification method is studied. The effects of the water temperature, water level and airflow rate on the humidification effectiveness, productivity and efficiency of the system were observed during the present experiments and the following points were concluded:

The productivity of the system increases with the increase of the water temperature and the decrease of the airflow rate. The productivity of the system is moderately affected by the water temperature and airflow rate and slightly affected by the water level. The humidification effectiveness is higher for Ma=14 kg/h at different water temperature and level. The efficiency of the desalination system is higher for Ma=12.6 kg/h and Ma=14 kg/h at different water level. At 80 °C, the productivity of the system is higher at different water level and airflow rate. The experimental measured agreed well with experimental calculation productivity. Within the studied ranges, the maximum productivity of the system reached to 0.81 kgw/kga at 87 °C for water and Ma=4.2 kg/h and Ma=8.4 kg/h.

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