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EXPERIMENTAL STUDY ON THE PERFORMANCE OF SOLAR WATER DISTILLATORY USING NOZZLE IMPINGEMENT

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Abstract— *In the present work, an experimental work had carried out on saline desalination using nozzle impingement with hot air stream. This work was done in Suez city, Egypt, 29.97 ° North 32.53 ° East 11 meters above sea level, from June to July 2016. Four horizontal nozzles were used with different nozzle diameters. Each nozzle has three holes that were drilled at an angle of 120° apart. Two condensers were used; an inclined surface with an angle of 5° to horizontal and the later one is a serpentine with a downward cold saline spray. A wire mesh was used in the humidification side to increase the saline evaporation rate. The effects of flow rate of saline, flow rate of the hot air stream, nozzle diameter and the existence of saline in the base of the humidifier were monitored. The fresh water productivity is 3.2 l/m^2 per day from 9.0 am to 3.0 pm.*

Keywords: Desalination, humidification dehumidification system, thermal systems, solar energy, water distillation.

NOMENCLATURE

Symbol	Description	Unit
A	Area	m^2
C	Specific heat	J / (kg. K)
H	Enthalpy	J/kg
$h_{fg.AV}$ $\dot{m}$	Latent heat	kJ/kg
h_{am}	Heat transfer coefficient with the ambient	W / (m^2. K)
I	Solar intensity	W / m^2
i	Current	A
k	Thermal conductivity	w / (m. K)
L	Length	m
$\dot{m}$	Mass flow rate	kg / s
n	Hours of operation	hr
P	Power	W
P_S	Water vapor pressure at surface temperature	Pa
P_w	Water vapor pressure at saline temperature	Pa
Q	Heat loss	W(J/S)
S	Salinity	g/kg
T	Temperature	K
U	Overall heat transfer coefficient	W / (m^2 . K)
V	Voltage difference	V
v	Velocity	m/s
W	Width	m
w	Moisture	$g/kg_{dry\ air}$

Greek letter

δ	Thickness	m
η	Efficiency	%
Ɛ	Emissivity	
σ	Stefan_Boltzman coefficient	$kW/m^2.k^4$

Subscripts

a	Air
ah	Air heater
am	Ambient
conv	Convection
csi	Cold saline inlet
f	Fresh water
hsi	Hot saline inlet
p+b	Pump and blower
pr	Productivity
rad	radiation
S	Surface
s	Saline
sc	Solar collector
so	Saline outlet
W	Wall

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1 INTRODUCTION

Desalination is the process of removing salinity from the sea water and is done by many ways centuries ago. Although desalination is important, but it consumes high energy; so many researchers have used solar energy as a source of heat in water desalination where the amount of solar radiation on a bright day is about 1000 watts per square meter. The following table (1) are some of the research works conducted to this field.

2 EXPRIMENTAL TEST RIG

Figure (1), shows a schematic diagram of the experimental test rig, the saline water was heated by an evacuated tube solar collector (HNZEN Vacuum Tube, SP-TG58-2100) has an area of 3 m2 and an inclination angle of 25°, as reported by [21]; the optimum tilt angle of solar collector in Egypt is ranging from 27.4° to 31.9° with an average of the residual angle of only 0.96° for 35 sites studied in the Mediterranean Region. The pumped hot saline is impinged through four horizontal nozzles as show in figure (2). They were located at a height of 20 cm above the base. One horizontal hot air stream (to prevent the saline water from falling inside the air duct) was fed into the room from 15 mm duct at a height of 15 cm above the base. Each nozzle has three holes at an angle of 120° apart. The hole diameter was varied to be 0.5, 1.0, 1.5, 2.0 mm as show in figure (3). The humid air was directed from the pyramid apex to the serpentine coil, figure (4). At the top of the test rig, an inclined condenser was used, it was exposed to ambient conditions. The fresh water from the serpentine and inclined condenser was collected in a pre-calibrated jar.

3 MATHEMATICAL MODELING

The electric power consumed for pump, blower and heater:

$$P = i \times V \quad (1)$$

Referring to figure (5), the system energy balance is as following to get the productivity rate.

$$\dot{m}_{hsi} C_{hsi} T_2 + \dot{m}_a H_{12} + \dot{m}_{csi} C_{csi} T_7 = \dot{Q} + \dot{m}_a H_5 + \dot{m}_f C_f T_6 + \dot{m}_{so} C_{so} T_{10} \quad (2)$$

The specific enthalpy of air H (kJ/kg) was determined as follows, as provided by [11];

$$H = 10.5 + 1.32 T_a + .00615 T_a^2 - 0.00106 T_a^3 + 2.82 \times 10^{-5} T_a^4 \quad (3)$$

The specific heat of the saline water was determined as follows, as provided by [22];

$$C = a_1 + a_2 T_s + a_3 T_s^2 + a_4 T_s^3 \quad (4)$$

$$a_1 = 4206.8 - 6.6197S + 1.2288 \times 10^{-2} S^2$$

$$a_2 = -1.1262 + 5.4178 \times 10^{-2} S - 2.2719 \times 10^{-4} S^2$$

$$a_3 = 1.2026 \times 10^{-2} - 5.5366 \times 10^{-4} S + 1.8906 \times 10^{-6} S^2$$

$$a_4 = 6.8774 \times 10^{-7} + 1.517 \times 10^{-6} S - 4.4268 \times 10^{-9} S^2$$

The heat loss Q (kW) Was determined as follows,

$$\dot{Q} = \dot{Q}_{conv} + \dot{Q}_{rad} \quad (5)$$

The heat transfer by convection between the surface or the side wall and the sky can be determined as follows, as provided by [2];

$$\dot{Q}_{conv1} = h_{ca} A_S (T_8 - T_{sky}) \quad (6)$$

$$\dot{Q}_{conv2} = h_{ca} A_W (T_9 - T_{sky}) \quad (7)$$

$$h_{ca} = 5.7 + 3.8 \times v_{am} \quad (8)$$

$$T_{sky} = T_{am} - 6.0 \quad (9)$$

The heat transfer by radiation between the surface or the side wall and the sky can be determined as follows, as provided by [2];

$$\dot{Q}_{rad1} = \varepsilon \sigma A_S \left[(T_8 + 273)^4 - (T_{sky} + 273)^4 \right] \quad (10)$$

$$\dot{Q}_{rad2} = \varepsilon \sigma A_W \left[(T_9 + 273)^4 - (T_{sky} + 273)^4 \right] \quad (11)$$

Comparing the theoretical results with the experimental results, it is clear that they are in agreement with parentage 96.2 % where the experimental productivity is 1.76 l/hr while the theoretical productivity is 1.83 l/hr.

The hourly efficiency (η_h) is calculated as follows as provided by [5]:

$$\eta_h = \frac{\dot{m}_f h_{fg.av}/3600}{A_{sc} I + P_{p+b}} \quad (12)$$

The average of the latent heat $h_{fg \cdot av}$ (J/kg) was determined as follows, as provided by [5];

$$h_{fg \cdot av} = 10^3 \times \left(2501.9 - 2.40706 T_{hsi} + 1.192217 \times 10^{-3} T_{hsi}^2 - 1.5863 \times 10^{-5} T_{hsi}^3\right) \quad (13)$$

Where $\dot{m}_f$ (kg/hr) is the fresh water productivity, A_{sc} (m^2) is the surface area of solar collector, I (W/m^2) is the solar intensity, P (W) is the power consumption.

3.1 Cost analysis:

The cost of production of one liter of fresh water varies from one season to another and from one day to another and from one hour to another, where productivity varies with time as shown in Figure (6). The cost is calculated as follows:

$$Cost/hr = \frac{cost_{s,fix}}{365 \times n \times \text{life time}} + cost_{op}/_{hr} \quad (14)$$

$$Cost/l = \frac{cost/hr}{pr/hr} \quad (15)$$

Where n (hr) is the hours of operation, life time (year) is the default age of the device, $cost_{s,fix}$ ($) is the cost of building the system, $cost_{op}/_{hr}$ ($/hr) is the operating cost per hour, pr/hr (L/hr) is the rate productivity per hour.

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Table (1) the some of the research works conducted to this field

Reference	Approach	Technique	Productivity	Location	Cost
[1]	Experimental and theoretical work	Humidification-dehumidification by using double-pass solar air heater and depended on the idea of closed water and open-air cycles.	2.3 L/hr	Ankara, Turkey	-
[2]	Experimental and theoretical work	Hybrid system by using humidification-dehumidification and solar stills integrated which works on the idea of reusing hot saline water.	66.3 L/day	Kafrelsheikh, Egypt	0.034 USD/l
[3]	Experimental and Analytical model	Humidification-dehumidification by using combined solar-geothermal energy which depended on heated the saline water by the geothermal energy and heated the air by the solar energy	104 L/m2	Madinah, Saudi Arabia	0.003 USD/L
[4]	Theoretical work	Hybrid system by using two stages of solar humidification–dehumidification and single stage flashing evaporation	112.5 L/day	Tanta city, Egypt	6.43 USD/m3
[5]	Experimental work	Humidification–dehumidification by using spray evaporation	9 L/m2	Suez University, Egypt	0.029 USD/l
[6]	Experimental and analytical model	Humidification–dehumidification which depended on heated the saline water by solar radiation with the aid of the external reflector and two water heaters immersed in the saline water.	30.3 L/m2	Madinah, Saudi Arabia	0.035 USD/L
[7]	Experimental work	Humidification-dehumidification with air conditioning system which consists of two circuits, one for refrigerant and the other for desalination.	4.74 L/h	Egypt	-
[8]	Experimental investigation	Two-stage solar humidification–dehumidification.	7.25 L/day · m2	Qom, Iran	-
[9]	Experimental and Theoretical work	Humidification-dehumidification by using by solar energy and low grade waste heat.	50 L/day	Al-Qassim, Saudi Arabia	0.014 USD/L
[10]	Theoretical work	Humidification-dehumidification by using a solar air heater and a solar water heater.	12 tons/year	Antalya, Turkey	-
[11]	Experimental and Theoretical work	Humidification-dehumidification by using a solar air heater and solar water heater and Photovoltaic (for electrical energy).	1.1173 L/h	Karabuk, Turkey	0.0981 USD/L
[12]	Experimental work	Cascade solar still coupled with a humidification–dehumidification system.	5.4 L/m2. day	Zahedan, Iran	-
[13]	Experimental, mathematical model and Simulator software	Multistage evacuated by using a solar operated vacuum pump.	$14.2 \frac{L}{m2}$/day	Malaysia	0.0254 USD /gallon
[14]	Experimental work	Solar still by using external solar collector and phase change material (PCM).	$4.3 \frac{L}{m2}$/day	Irbid, Jordan	-
[15]	Experimental work	Water desalination system by using vacuum type heat exchanger.	$1.5 \frac{L}{m2}$/day	Tehran, Iran	-
[16]	Experimental work	Humidification–dehumidification with the use of a cylindrical surface exposed to air as a distillation.	$9 \frac{L}{m2}$/day	Makkah Saudi Arabia	0.5 USD/L
[17]	Numerically	Hybrid system includes humidification–dehumidification unit and flashing evaporation unit.	$11.14 \frac{L}{m2}$	Tanta, Egypt	-
[18]	Experimental work	Humidification–dehumidification unit with indirect evaporative air cooler.	47.21 l/day	Tanta, Egypt	-
[19]	Experimental and theoretical work	Humidification–dehumidification by using a hollow fiber membrane as a humidifier.	$25.88 \frac{L}{m2}$/day	China	-
[20]	Experimental work	Humidification–dehumidification by using air bubble column.	21 L/day	Tanta, Egypt	-

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3.2 UNCERTAINTY ANALYSIS

The uncertainty analysis was determined as follows, as provided by [23];

$$\eta_h = \frac{m_f h_{fg.av}}{A_{sc} I + (iv)_{p+b}} = 0.277 \quad (16)$$

$$A_{SC} = L \times w \quad (17)$$

$$\frac{\partial A_{SC}}{\partial L} = w \quad (18)$$

$$\frac{\partial A_{SC}}{\partial w} = L \quad (19)$$

$$\Delta A_{SC} = \sqrt[2]{\left(\frac{\partial A_{SC}}{\partial L}\Delta L\right)^2 + \left(\frac{\partial A_{SC}}{\partial w}\Delta w\right)^2} = 2.5 \times 10^{-3}\ m^2 \quad (20)$$

$$\frac{\partial \eta_h}{\partial \dot{m_f}} = \frac{h_{fg.av}}{A_{sc} I + (iv)_{p+b}} = 0.15\ \frac{s}{kg} \quad (21)$$

$$\frac{\partial \eta_h}{\partial h_{fg.av}} = \frac{\dot{m_f}}{A_{sc} I + (iv)_{p+b}} = 1.12 \times 10^{-7}\ kg/j \quad (22)$$

$$\frac{\partial \eta_h}{\partial A_{sc}} = \frac{-\dot{m_f} h_{fg.av} \times I}{(A_{sc} I + (iv)_{p+b})^2} = -0.051\ \ (m^2)^{-1} \quad (23)$$

$$\frac{\partial \eta_h}{\partial I} = \frac{-\dot{m_f} h_{fg.av} \times A_{sc}}{(A_{sc} I + (iv)_{p+b})^2} = -1.81 \times 10^{-4}\ \frac{m^2}{w} \quad (24)$$

$$\frac{\partial \eta_h}{\partial i_{p+b}} = \frac{-\dot{m_f} h_{fg.av} \times v_{p+b}}{(A_{sc} I + (iv)_{p+b})^2} = -0.013\ (Amb)^{-1} \quad (25)$$

$$\frac{\partial \eta_h}{\partial v_{p+b}} = \frac{-\dot{m_f} h_{fg.av} \times i_{p+b}}{(A_{sc} I + (iv)_{p+b})^2} = -4.99 \times 10^{-4}\ (volt)^{-1} \quad (26)$$

$$\Delta\eta_h = \sqrt[2]{\left(\frac{\partial \eta_h}{\partial \dot{m_f}}\Delta \dot{m_f}\right)^2 + \left(\frac{\partial \eta_h}{\partial h_{fg.av}}\Delta h_{fg.av}\right)^2 + \left(\frac{\partial \eta_h}{\partial A_{sc}}\Delta A_{sc}\right)^2 + \left(\frac{\partial \eta_h}{\partial I}\Delta I\right)^2 + \left(\frac{\partial \eta_h}{\partial i_{p+b}}\Delta i_{p+b}\right)^2 + \left(\frac{\partial \eta_h}{\partial v_{p+b}}\Delta v_{p+b}\right)^2} \quad (27)$$

$$U\eta = \frac{\Delta\eta_h}{\eta_h} = \frac{0.0015}{0.277} = \pm 0.005 = 0.5\ \% \quad (28)$$

Table (2) the cost of the system.

Component	*Cost*
Evacuated tube solar thermal	*550$*
Humidification-dehumidification unit	*220$*
Pump	*42$*
Blower with heater	*36$*
Water tank	*11$*
Insulated pipes	*30$*
Measuring jar	*3$*
Valves	*14$*
Measuring device	*147$*
Total cost	*1053$*

Table (3) the measuring devices.

Instrument	Measuring	Range	Accuracy
Anemometer	Air velocity	(0.0 – 15 m/s)	±0.1 m/s
Hygrometer	Relative humidity	(0.0 – 100 %)	±1 %
Solar power meter	Solar radiation	(0.0 – 1999 W/m²)	±10 W/m²
Pressure gauge	Pressure of saline water	(0.0 – 7.0 bar)	±0.125 bar
Voltmeter	Voltage	(0.0 –750 volt)	± 0.1 v
Ammeter	Current	(0.0 – 20 Amb)	± 0.01 A
Pre-calibrated measuring	Fresh water	(0.0 – 3 L)	0.01 L
Rotameter	Water flow rate	(0.2 - 4.9 L/min)	

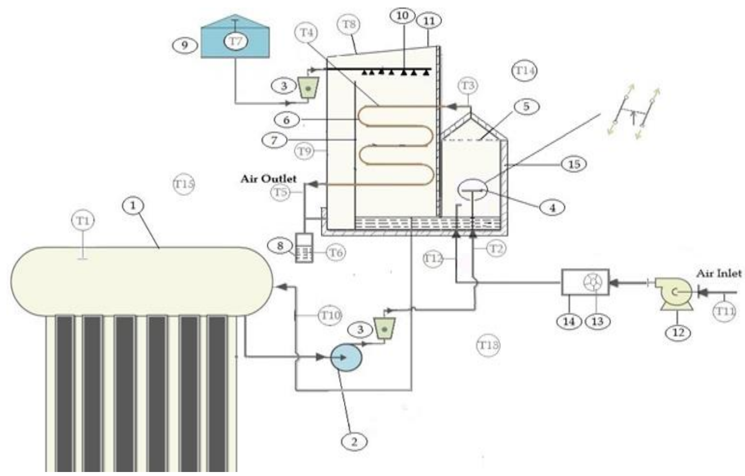

Fig (1), Schematic diagram of experimental test rig.

1- Evacuated tube solar collector tank
2- Water pump
3- Water rotameter
4- Nozzles
5- Steel wire mesh
6- Condenser serpentine coil
7- partition steel plate
8- Pre-calibrated jar
9- Insulated tank for cold saline
10- Sprinkler
11- Inclined condensate surface
12- Blower with heater
13- Air velocity gauge anemometer
14- Insulation
T1- Collector tank temperature
T2- Saline supply temperature to humidifier
T3- Supply humid air temperature to condenser coil
T4- Condenser coil temperature
T5- Outlet air temperature
T6- Fresh water temperature
T7- Cold saline temperature in the tank
T8- Condenser surface temperature
T9- Wall temperature
T10- Saline inlet temperature to collector
T11- Supply temperature air to the blower
T12- Supply hot air temperature to the humidifier
T13, T14, T15- Ambient temperature

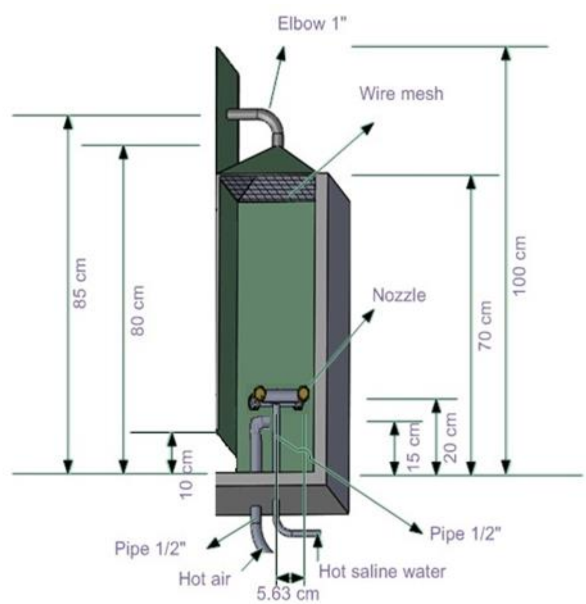

Fig (2), Isometric of the Humidification room.

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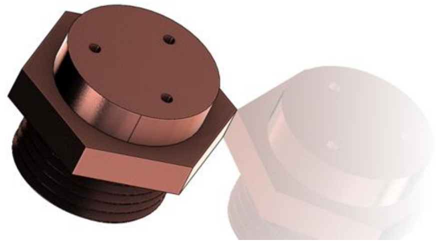

Fig (3), Isometric of the nozzle

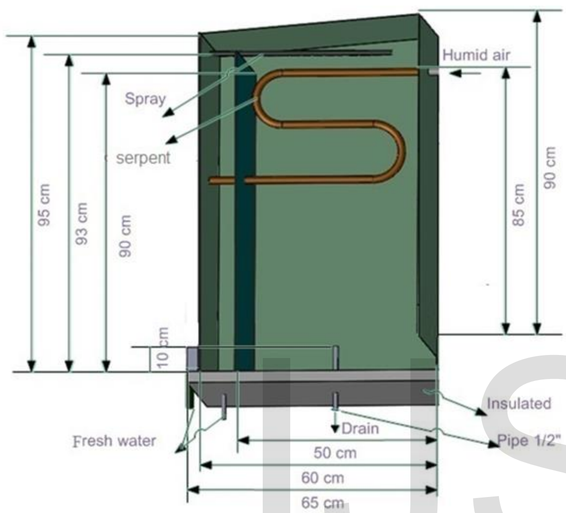

Fig (4), Isometric of the dehumidification room.

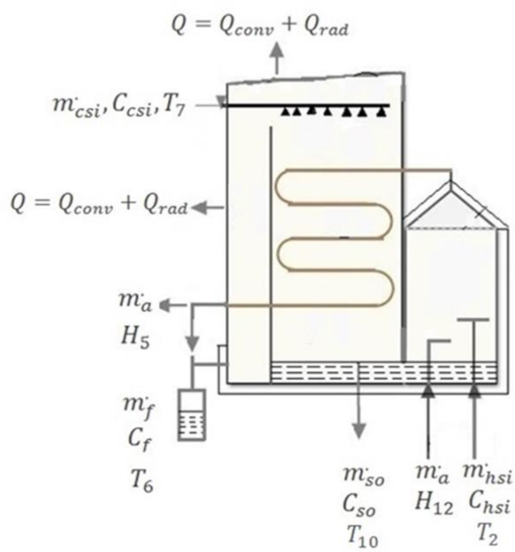

Fig (5), Schematic diagram for the system energy balance

4 RESULTS AND DISCUSSION

During the practical study of the system, it was found that

- In figure (7), It is clear that the optimum diameter is 1 mm as it increases the pressure difference between the exit of the nozzle and the entrance of the humidifier compared to each diameters (1.5 mm, 2mm) It is also less durable than the diameter (1/2 mm).
- In figure (8), It is clear that productivity increases with an increase in the flow rate of hot saline as the higher the speed of hot saline the less the internal pressure.
- In figure (9), Increasing productivity with increasing air temperature where the low temperature of the air for a certain value lead to the opposite result as it works on condensed water vapor in humidifier.
- In figure (10), It is clear that the temperature continues to increase until 2 pm, despite the decrease in solar radiation. This is due to the solar collector, where it maintains a large amount of heat without loss and also due to the amount of heat needed compared to the amount of radiation given.
- Figure (11), shows that efficiency continues to increase until 3 pm as it depends on the amount of energy consumed compared to productivity.
- Figure (12), shows a comparison between the current work and some previous work. Where it is clear that the current productivity rates are lower than Nafey, [24] where he uses a system of surfactant additives to brine and higher than Deniz, [11]; where it works at lower flow rates of salt water and there is convergence of Tabrizi, [12] and depends on the work on the natural circulation without pumping.

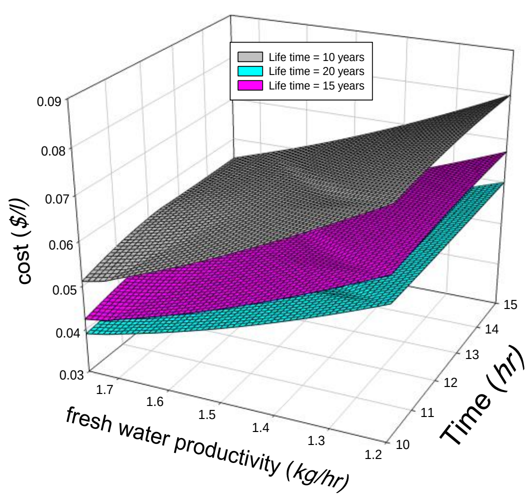

Figure (6), 3-D, Time variation of the cost and productivity.

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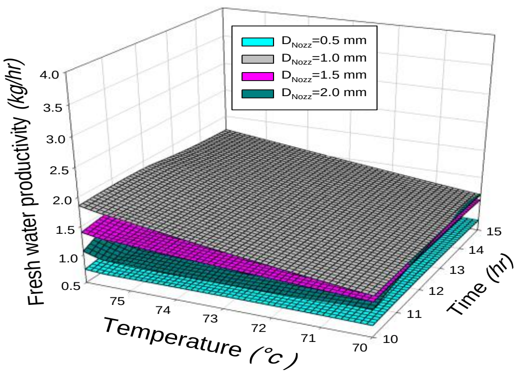

Figure (7), 3-D, Time variation of the temperature and productivity at the same saline flow rate.

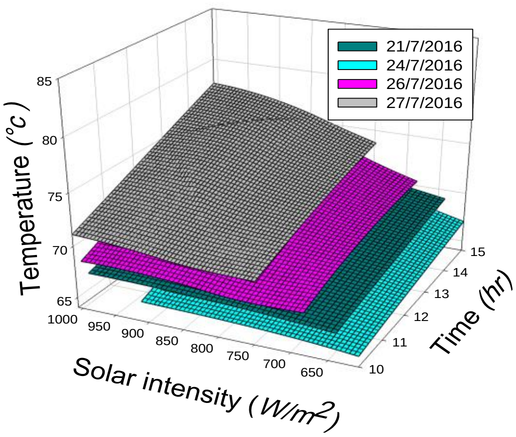

Figure (10), 3-D, Time variation of the temperature and solar intensity.

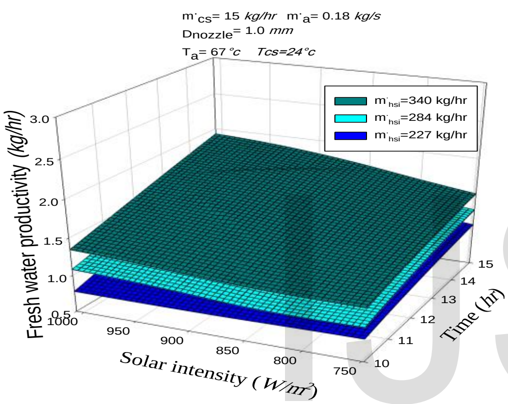

Figure (8), 3-D, Time variation of the solar intensity and productivity at the same nozzle diameter.

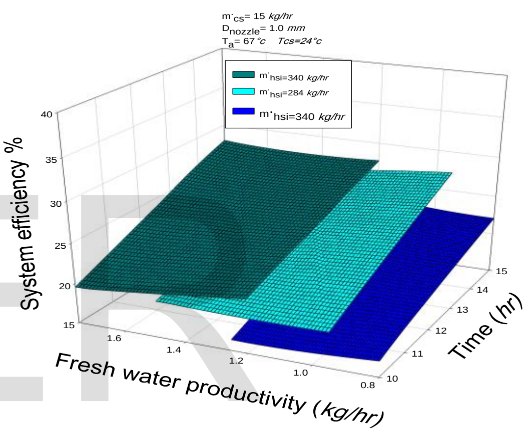

Figure (11), 3-D, Time variation of the system efficiency and productivity at the same nozzle diameter.

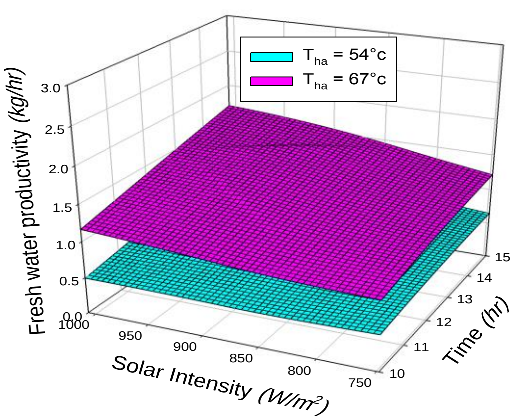

Figure (9), 3-D, Time variation of the solar intensity and productivity at the same nozzle diameter and saline flow rate.

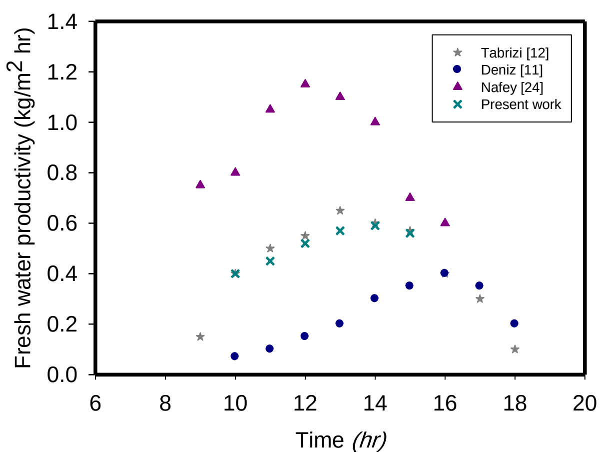

Figure (12), Comparison between current work and some previous work.

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5 CONCLUSION

Through the practical study on saline desalination using nozzle impingement, the following conclusions were made:

- The rate of productivity increases with the existence of saline in the base of the humidifier and a wire mesh.
- The higher the air speed on a certain limit, the less productive.
- The productivity increases with the increased flow rate of hot saline water.
- Diameter 1 mm is the optimum diameter for increasing productivity.
- The higher the temperature of the air the greater the evaporation rate and the less speed of the air.
- In this case, condensation using the coil and water spray is less successful than other condensation methods.
- The system productivity rate is 3.2 L/m^2 where daily working hours are 6 hours from 9 am to 3 pm and the evacuated tube solar collector has a storage tank 200L, surface area is 3 m2.
- The cost per liter is (0.04 $/L) at the high production (1.76 kg/hr) and the efficiency is 27.7% in the same production.

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