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Solar Desalination by Evaporation-Condensation Process

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Conventional desalination technologies
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ABSTRACT

World-wide water scarcity, especially in the developing world, indicates a pressing need to develop inexpensive, decentralized small-scale desalination technologies which use renewable resources of energy. However, conventional desalination technologies are usually large-scale, technology intensive system most suitable for the energy rich and economically advanced regions of the world. They also cause environmental pollution because they are fossil fuel driven and also because of the problem of brine disposal. Solar desalination with a evaporation and condensation process has proven to be an efficient means of utilizing solar energy for the production of fresh water from saline or sea water. This study presents several advantages such as flexibility in capacity, moderate installation and operating costs, simplicity, and possibility of using low temperature energy such as geothermal and solar. In this paper, the objective is to experimentally install a solar desalination prototype applies evaporation and condensation principle with minimum low cost of fresh water production and also simplicity in terms of the technology applied. Thus, through this study and prototype installation, which will be a platform to drive the commercialization of a solar desalination based on evaporation and condensation principle due to incoming short fresh water supply in future especially for small quantities in remotes. The results of study show that a total mass transfer of a fresh water production of 0.00312 L/min. Also the average thermal efficiency of process is 34%. Moreover, the efficiency of evaporator and condenser are 37% and 6% respectively.

تحلية المياه بالطاقة الشمسية عن طريق عملية التبخيروالتكثيف

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الكلمات المفتاحية:
التلوث البيئي
الطاقة الشمسية
تحلية المياه بالطاقة الشمسية بعملية التبخر والتكثيف
تقنيات التحلية التقليدية.

الملخص

تشير ندرة المياه في جميع أنحاء العالم، لا سيما في العالم النامي، إلى حاجة ملحة لتطوير تقنيات تحلية مياه غير مكلفة ولا مركزية على نطاق صغير تستخدم موارد الطاقة المتجددة. ومع ذلك، فإن تقنيات تحلية المياه التقليدية عادة ما تكون واسعة النطاق، ونظام كثيف التكنولوجيا الأنسب للمناطق الغنية بالطاقة والمتقدمة اقتصاديًا في العالم. كما أنها تسبب تلوثًا بيئيًا لأنها مدفوعة بالوقود الأحفوري وأيضًا بسبب مشكلة التخلص من المحلول الملحي. أثبتت تحلية المياه بالطاقة الشمسية مع عملية التبخر والتكثيف أنها وسيلة فعالة لاستخدام الطاقة الشمسية لإنتاج المياه العذبة من المياه المالحة أو مياه البحر. تقدم هذه الدراسة العديد من المزايا مثل المرونة في السعة، وتكاليف التركيب والتشغيل المعتدلة، والبساطة، وإمكانية استخدام الطاقة منخفضة الحرارة مثل الطاقة الحرارية الأرضية والطاقة الشمسية. في هذه الورقة، الهدف هو تركيب نموذج تجريبي لتحلية المياه بالطاقة الشمسية يطبق مبدأ التبخر والتكثيف مع الحد الأدنى من التكلفة المنخفضة لإنتاج المياه العذبة وكذلك البساطة من حيث التكنولوجيا المطبقة. وبالتالي، من خلال هذه الدراسات وتركيب النماذج الأولية، والتي ستكون منصة لدفع تسويق تحلية المياه بالطاقة الشمسية على أساس مبدأ التبخير والتكثيف بسبب نقص إمدادات المياه العذبة الواردة في المستقبل خاصة بالنسبة للكميات الصغيرة في أجهزة التحكم عن بعد. تظهر نتائج الدراسة أن إجمالي نقل الكتلة لإنتاج المياه العذبة يبلغ 0.00312 لتر/دقيقة. كما أن متوسط الكفاءة الحرارية للعملية هو 34 ٪. علاوة على ذلك، تبلغ كفاءة المبخر والمكثف 37 ٪ و 6 ٪ على التوالي.

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1. Introduction

The Renewable energy has become a vital source of power in our daily life due to its availability without pollution side effects. Renewable energy is used in several applications. One important example of such energy sources solar energy that used in water desalination Fossil Fuels received their solar input eons ago and have changed their characteristics so that they are now in a highly concentrated form. Since it is apparent that these stored concentrated energy forms are now being used at such a rapid rate the they will be depleted in the future. The word must begin to supply a large portion of our energy needs not from fossil stored energy, but from incoming solar energy which renewable and environmental friendly [1].

There are several desalination technologies, that use different separation principles, these technologies such as:

- Conventional Desalination Technologies
- Limitations of Conventional Technologies
- Evaporation and Condesation (EC) Desalination

2. Solar Energy

The energy is considered to be one of the most important factors that could affect the economics of the world countries. The growth of technology in the second half of the last century. Caused an increase in the energy consumption. This shows the possibility of the limited of the fossil fuel in future. The consequences would lead to threatening the civilization and population. The world begins to search for a new source of energy. Hence, the importance of solar energy takes place for its over abound presences and that it makes enough great abilities to face our needs for millions of years. This makes solar energy the main energy of the future, and imposed to us to conduct deep research study in solar energy and its applications. As we know that our Arab land is rich of this energy, we can know that when we explore a time period of sun shining hours on Arab countries, then we find that it is high in many Arab countries to equal ten months per a year. This economic value for solar energy received motivate us to be more active to do research study and think to convert it to another type of energy as heat energy, mechanical energy and electrical energy.

3. Renewable Energy Desalination

In the water cycle, the sun's solar irradiation evaporates a portion of the ocean's surface water and the water vapor rises humidifying the surrounding air which acts as a carrier gas. The evaporator air rises, convicts and condenses forming clouds. The clouds then are condensing in the form of rain.

4. Evaporation Condensation (EC)

The predecessor of the EC cycle is the simple solar still. The solar still is similar to a greenhouse system in the manner in which it captures the solar energy. The incident solar radiation is transmitted through the glass cover or similar transparent material having the property of transmitting incident short-wave solar radiation and it is absorbed as heat by a black surface in contact with the salt water in the basin of the still. Some of the water evaporates and the water vapour condenses on the surface of the solar still, which is at a lower temperature because it is in contact with the ambient air.[5]. Solar stills have the advantage of ease of construction and maintenance. However, they have several disadvantages. The most prohibitive drawback of a solar still is low efficiency. For a solar still the GOR is less than 0.5. Thus, large areas of land are required to produce relatively small amounts of water.

5. Classification of Evaporation Condensation(EC)Processes

EC systems are classified into three broad categories. One category is based on the source of energy used, such as renewable energy. For example, solar thermal E-C or hybrid E-C. The second classification is based on the cycle configuration. There are two main types of E-C cycles: closed-water, open-air (CWOA) cycle and closed-air, open-water (CAOW) **Figure (1)**. An open-water, open-air cycle is also possible but since it has a lower thermal efficiency than the other two cycles, it will not be discussed. The air in these systems is circulated by natural or forced convection (fans). The air is heated and loaded with moisture as it passes upwards through the falling hot water in the evaporation chamber. After passing through a condenser cooled with cold seawater, the partially dehumidified air leaves the unit, while the condensate (distillate) is collected. The water is recycled or recirculated. Incoming cold air provides a cooling source for the circulating water before it re-enters the condenser. The productivity of units working on this principle is high, but the power required for air circulation is also very high [6].

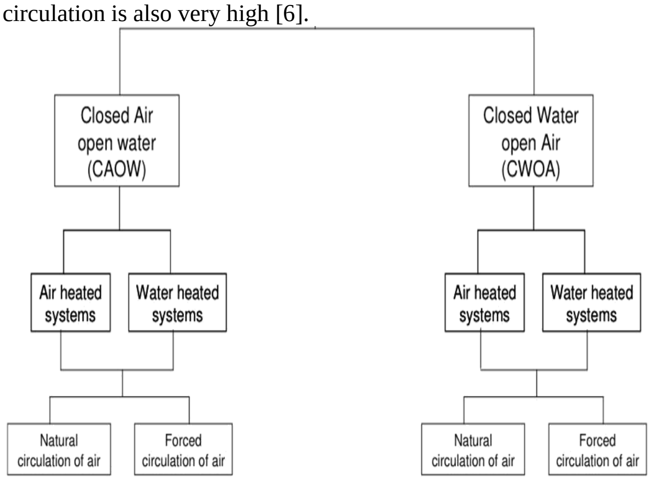

Fig. 1: EC cycles [4]

The third classification of EC processes is based on whether the air or the water is heated. The performance of the system heavily depends on whether the air or water is heated. There is extensive knowledge of solar water heating devices but relatively little work has been done on air heating solar collectors. Typically, air-heated systems have higher energy consumption than water-heated systems because in the air-heated cycle the air heats up the water in the evaporator and this energy is not subsequently recovered from the water. On the other hand, in the water-heated cycle, the water stream is cooled in the condenser and the energy is transferred or recovered in the air stream. Enhanced latent heat recovery is needed to minimize the energy consumption and the resulting cost of these cycles[4]. **Figure (2**) shows the different EC cycle combinations discussed above [4].

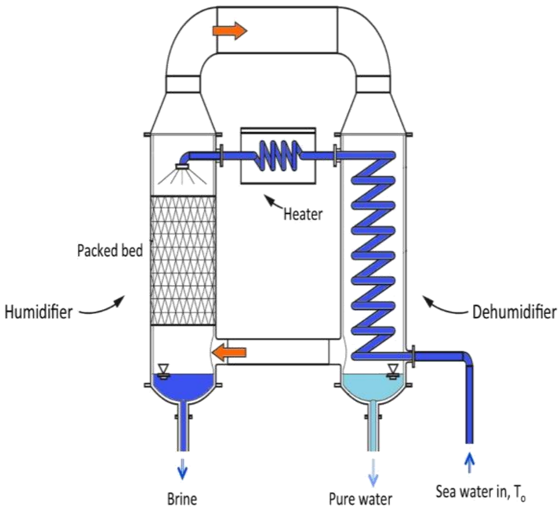

Fig.2: *E C unit with closed-air/open-water cycle [4]*

The main objectives of the present investigation are:

1. Presents a principle of Evaporation Condensation (EC) desalination processes with a water-cooling condenser.
2. Examine experimentally the solar EC processes under different real weather and operating conditions.
3. Examine the effect of system configurations on the system productivity and the influence of different weather, operating and design parameters on the system productivity.

6. Experimental Work

This experiment was conducted near the Faculty of Engineering in Sabratha on longitude and latitude lines (Longitude line: 12.5^o, Latitude Line: 32.8^o). The experiment was conducted in the fall of the year (2020) and the research period lasted for six months. The temperature was measured by the Thermocouples scale shown in **Figure (4)** and the humidity by the humidity sensor shown in **Figure (5)**. The air flow rate was measured by the Digital air and speedometer shown in **Figure (6)** as well as the water flow rate measured by the Dwyer shown in **Figure (7)**. The wind speed and solar radiation intensity were measured by the Pyranometer. All measurements were made within a time period of (a quarter of an hour) for each flow rate of water and air in the system shown in Figure (3). All the results of the measurements mentioned above are shown in **Tables (1-4)**, through which the calculations were made, which led to the production of approximately (0.00312 ml/min) of desalinated groundwater, with a thermal efficiency of 34% and an efficiency of 37% for the evaporator, and 6% for the condenser.

7. Apparatus Overview

The apparatus can be considered in terms of the column, water loop, air loop and the measuring devices. The air loop consists of the fan, the air distribution channel. The water loop consists of the water distribution system, the droplet arrester or drift eliminator and the basin. Refer to **Figure (3-a, 3-b)** for the schematic of the solar EC processes and temperature measurement location. The column dimensions are 400 mm diameter and 1500 mm high; the column was constructed with to be an open channel without a bed.

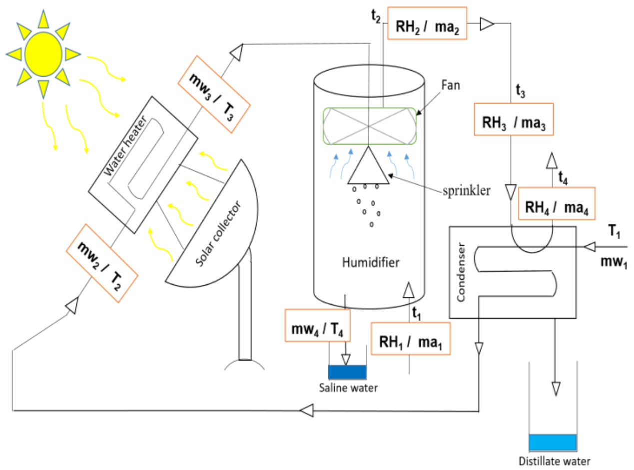

***Fig. (3-a,3-b)**: solar desalination unit with a evaporation and condensation cycle*

8. Water Loop

The water loop is an open water loop, taking warm water from the sink, through the water flow meter or control valve, to the column cap where its temperature is measured before it is sprayed over the packing through the water nozzle. The water is uniformly distributed at the top of the column and as it spreads over the column, a droplet of water is exposed to the air stream. During its downward passage through the column, the water is cooled, largely by the evaporation of a small portion of the total flow. The cooled saline water falls into the basin, from where it flows past a thermocouple and into the load tank, where it exits to the drain. A Dwyer rotameter is used to measure the water flow rate.

Air Loop

C. Air Loop

Air from the atmosphere enters the fan at a rate that is controlled by the intake damper setting. The ambient air conditions have a significant effect on the cooling tower performance. The fan forces the air into the distribution chamber and the air passes wet and dry bulb thermocouples before it enters the packed column. As the air stream flows through the fill, its moisture content increases and the water is cooled. On leaving the top of the column, the air passes through the drift eliminator, which traps most of the entrained droplets and returns them to the fill. The air is then discharged to the atmosphere via the air-measuring orifice at the tower outlet. The air passes wet and dry bulb thermocouples before it exits the tower. The air mass flow rate (G) is measured by a pressure differential across the air exit orifice, connected to an inclined manometer.

9. Measurement and instrumentation

All measurements were taken each fifteen-minute including the solar intensity, wind speed, and the air velocity in the column which taken at the middle. The air dry and wet bulb temperatures at the inlet and outlet of the column, as well as the temperatures of the water at inlet and outlet, are measured with a digital temperature indicator with a thermocouple selector switch.

10. Instrumentation

- Temperatures measurement**:** Two pairs of wet and dry-bulb Omega type 'T' thermocouples as shown in **Figure (4)** for air entry and exit from the tower respectively. Two type 'T' Omega thermocouples for water entry and exit to tower. Thermocouples have an ambient reference temperature connected to the interface directly. Refer to Figure 3 for thermocouple locations.

***Fig. 4:** Thermocouples*

- Humidity measurement: air humidity is measured at each point on the air loop using a digital humidity sensor as shown in **Figure (5)**.

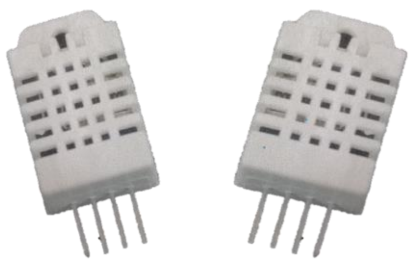

Fig. 5: humidity sensor

- Air flow rate measurement: a digital air flowmeter as shown in **Figure (6-a)** is used to measure the air flow rate inside the humidification tube, while a speedometer is used to measure the speed the atmospheric air as shown in **Figure (6-b)**.

a b

***Fig. 6:** digital air flowmeter (a), speedometer (b)*

- Water flow rate measurement**:** The Dwyer rotameter as shown in **Figure (7)** is used to indicate the water flow rate.

***Fig. 7**: Dwyer rotameter*

11. Working procedure

A solar desalination unit with an evaporation and condensation cycle, which is configured mainly by a solar collector, evaporator and condenser, is shown in **Fig. (3)** Saline water is heated up to T_4 by plate heat exchanger (Radiator) installed on a solar collector which receives solar energy and turns it to thermal energy, and then is sprayed to downward the column evaporator by a sprinkler to saturate the air. Driven by a fan, the process air is forced to pass through the evaporator where it becomes hot and humid because of the heat and mass exchange between saline water and wet air. Then the process air passes through the condenser and cooled by cooling water where water vapor in the air is condenses and turns into fresh water. Moist air out of the condenser becomes humid and cold and sent to the atmosphere. Cold saline water flows in the tube channel and fresh water is produced on the condensation surface in the condenser at the same time. The remaining saline water drawn from humidifier becomes cold and is collected at the bottom basin. The warm cooling water comes out of the condenser is fed to the solar collector Radiator, in this way the fresh water can be produced continually and the heat recovery is included.

12. Results and discussion

12.1. Experimental result

During the experiment operation all the results have been taken periodically each fifteen minute for two hours including both, water and air loops.

Table (1) shows the recorded result of measuring instruments for the water temperature in each point of the water loop.

Table 1: Temperatures of several points in water loop

Time(min)	T1	T2	T3	T4
15	19.0	42.5	28.9	29.1
30	24.6	42.3	28.9	29.2
45	27.7	42.0	29.1	29.7
60	26.7	42.1	30.3	30.3
75	28.5	42.7	29.7	28.8
90	27.4	42.5	29.7	28.9
105	26.7	42.0	29.5	28.5
120	26.2	41.1	28.9	28.3

Table (2) shows the results for the water flow rate into the system (V1), wind speed at the inlet (VC2) and outlet (VP) of the evaporator, and solar intensity (Q1).

Table (2): Solar intensity,air and water flow rate

Time (min)	V1 (L/min)	VC2 (m/s)	VP (m/s)	Q1 (W/m^2)
15	0.246	1	1.2	672
30	0.246	1.2	1.2	684
45	0.246	0.58	1.2	691
60	0.246	0.76	1.2	681
75	0.246	0.92	1.2	665
90	0.246	1.28	1.2	651
105	0.246	1.44	1.2	629
120	0.246	0.56	1.2	602

Table (3) shows the recorded result of measuring instruments for the air temperature in each point of the air loop.

Table 3:Temperatures of several points in air loop

Time(min)	T_1	T_2	T_3	T_4
15	35.71	21.28	27.25	34.18
30	34.79	20.71	27.29	33.72
45	34.48	20.56	27.20	33.40
60	34.28	21.13	27.36	33.54
75	34.91	21.84	28.22	34.68
90	34.11	20.82	28.36	34.12
105	33.75	21.10	28.01	33.36
120	33.45	20.79	27.74	33.13

Table (4) shows the experimental results of relative humidity for the air at each point of the air loop system.

Table 4: Humidity of several points in air loop

Time(min)	RH_1	RH_2	RH_3	RH_4
15	70.58	99.90	99.90	97.34
30	69.87	99.90	99.90	97.24
45	66.72	99.90	99.90	97.89
60	61.47	99.90	99.90	99.03
75	58.12	99.90	99.90	98.95
90	59.48	99.90	99.90	96.55
105	59.38	99.90	99.90	98.67
120	58.67	99.90	99.90	98.21

12.2. Estimation of thermal efficiency

The modes take into consideration. There are several Empirical models can be used to estimate the thermal efficiency of several processes, the thermodynamic relations have been used to describe the flow, heat and mass transfer inside the evaporator, condenser, and water solar collectors. A set of algebraic equations has been considered and solved manually, and the following assumptions are considered: (i) the feed water, cooling water and feed air have constant flow rates along the day. (ii) Thermal losses due to the ambient are neglected. (iii) The thermal analysis is assumed in quasi-steady condition.

12.3. Material balance and energy balance calculation

The material and energy balance for all equipment are made under steady state condition as well as there is no mass or heat losses.

- **Solar energy collector**

  The water flow rate that comes from the source and entering the solar collector is measured using flowmeter to be 0.246 L/min. assuming the water density of 1 kg/L. The mass flow rate of water entering the collector can be calculated as:

  $$mw_2 = 0.246 * (1/60) = 0.0041 \text{ kg/s}$$

  Since the processes taken in steady state condition and there is no water losses, the mass balance around the solar collector becomes:

  $$mw_2 = mw_3 = 0.0041 \text{ kg/s}$$

  To calculate the actual heat input that carried by the water passing throughout the solar collector, the energy balance around the solar water collector is performed under steady state conditions and assuming that no energy losses to the atmosphere, so that the actual heat input to the system is calculated at each time interval by:

  $$Q_{act} = mw_3*H_3 - mw_2*H_2 \quad (1)$$

  Since the process is steady state so, the mass in is equal the mass out and the equation (Eq.1) become:

$$Q_{act} = mw_2 (H_3 - H_2) \quad (2)$$

Because there is no phase change, the enthalpy change of the water can be calculated using the heat capacity of water. Since the temperature difference of the water is not too high, so the heat capacity of water can be assumed constant and taken as 4.18 kJ/kg.K and the Eq.2 becomes:

$$Q_{act} = mw_2*\mathbf{C}p*(T_3 - T_2) \quad (3)$$

Using equation (Eq.3) and data in table 1 the amount of actual heat input to the system (Q_{act}) is calculated for each time interval and the results are shown in **Table (5)**.

Table 5: Estimated value for actual heat input to the system

Time(min)	T2	T3	Q_T (W)	Q_{act} (W)
15	29.1	42.5	672	229.3133
30	29.2	42.3	684	224.8308
45	29.7	42.0	691	211.6082
60	30.3	42.1	681	201.9054
75	28.8	42.7	665	238.9762
90	28.9	42.5	651	232.5561
105	28.5	42.0	629	231.4289
120	28.3	41.1	602	218.5661

- **Evaporator**

  The mass balance is made around the evaporator in order to calculate the rate of evaporation along the evaporator which is equal to the amount of water that carried by the flowing air using the following equation:

  $$ER = ma_1(w_2 - w_1) \quad (4)$$

  Where: ER is the rate of evaporation, ma1 is the mass flow rate of the inlet air, w_2 and w_1 are water content in the air at the inlet and outlet of evaporator respectively

Mass flow rate of air inside the evaporator is calculated by following equation:

$$ma_1 = \rho * v * A \quad (5)$$

Where: ρ is the air density, v is the air flow rate, A is the cross-section area of the humidifier.

ρ = 1.1817 kg/m^3

v = 0.1278 m/s

A=0.049087 m^2

ma_1 = 1.1817*= 0.1278*0.049087 = 0.00741 kg/h

- **Condenser**

Since the condenser is working in steady state mode, so the mass balance shows that for the water stream has the same flow rate at the inlet and outlet where it is calculated previously to be:

$mw_1 = mw_2$ = 0.0041 kg/s

The steady state mass balance for the air stream was made to evaluate the rate of condensation which calculated by:

$$CR = ma_3 * (w_4 - w_3) \quad (6)$$

Where: CR is the condensation rate, ma_3 is the air flow rate, w_3 and w_4 are the water content of the air at stream 3 and stream 4 respectively.

CR = 0.0074*(0.03535 – 0.0333) = 0.00001517 kg of water

12.4. System efficiency calculation

Two coefficients to evaluate the system performance are defined: thermal efficiency and water productivity. Thermal efficiency stands for the ratio of the amount of useful energy to total heat input per unit time per unit surface to receive solar irradiation; in other words, it is the ratio of the minimum energy to obtain a fixed amount of water to the practical heat input

$$\eta = \frac{Q_{act}}{Q_T} \quad (7)$$

Here, Q_{act} is actual heat input to the water, and Q_T is solar intensity. Particularly, the reason that this unit does not adopt the conventional productivity is due to the different configuration of the condenser.

The average value of efficiency is calculated using data in table and equation (Eq.7)

$$\eta = 34\%$$

- **Evaporator**

The efficiency of the humidifier is measured by the increase of the relative humidity of the air along the humidifier, which is calculated by:

$$\text{Eff.} = RH_2 - RH_1 \quad (8)$$

Where: RH_1 and RH_2 are the relative humidity at the inlet and outlet of the humidifier respectively.

Using data from **Table (4)** and eq.8 the efficiency is calculated at each time interval and the results are shown in the **Table (6)**.

Table (6): Efficiency calculation for humidifier

TIEM	RH1	RH2	Eff.
15	70.576	99.9	29.32
30	69.86923	99.9	30.03
45	66.71538	99.9	33.18
60	61.46538	99.9	38.43
75	58.12308	99.9	41.78
90	59.48462	99.9	40.42
105	59.38462	99.9	40.52
120	58.66667	99.9	41.23
	Average		36.86

The average value of the thermal efficiency is than calculated to be about 37%.

- **Condenser**

The efficiency of dehumidifier is measured by how much water is condensed from the air relative to the inlet amount and it is calculated by:

$$\eta = \left|\frac{w_4 - w_3}{w_3}\right| \quad (9)$$

$$\eta = \frac{0.0333 - 0.03535}{0.03535}$$

$$\eta = 6\%$$

12.5. Water productivity

Different from the productivity of a conventional solar still, which is water production per unit time per unit surface of condenser, water productivity (W_P) here stands for the water production per unit time per unit surface to receive solar irradiation, and represents the ability for this desalination unit to produce water.

Taking the time interval 15 minute and 1m^2 as surface to receive solar irradiation, the water productivity is calculated by the following equation:

$$W_P = \frac{w_3 - w_4}{1m^2 * 15\ min.} = \frac{0.03535 - 0.0333}{1m^2 * 15\ min.} = 0.000137\ \frac{kg}{m^2 * min}$$

Taking the water density $1000\ \frac{kg}{m^3}$ the volume of water produced is calculated to be

$$w_p = 0.13\ \frac{ml}{min.}$$

13. Conclusion and Recommendation

13.1. Conclusion

RE-desalination generally, and E-C in particular, have a critical role to play in meeting the world's rapidly increasing water demands. For RE-desalination to become widely spread, it must overcome technological, social, economic, political and environmental barriers. Key factors to surmount these barriers are RE-desalination research and development (R&D), market signals that reduce the perceived risks associated with RE-desalination and effective action by the appropriate stakeholders for raising RE-desalination awareness and growth.

The Evaporation-Condensation (E-C) process presents a very interesting solution for small units (hotels, rural regions, light industry, etc., especially when new materials are used. The process is very convenient in cases where heat is available at low temperature at an attractive cost (cogeneration, solar energy, geothermal energy, etc.

After 6 months of research and prototype installation, the test run for the prototype was conducted and succeeded to produce 0.00312 L/min of desalinated groundwater. Thus, the objective is achieved with the average thermal efficiency of 34%. Moreover, the efficiency of evaporation-condensation was estimated to be 37% and 6% respectively. This project can be a platform for university of Sabratha to start researching on solar-driven desalination and in future to commercialize this desalination concept in Libya.

13.2. Recommendations

Based on the results that have been obtained, many recommendations can be made for further research and improvements.

1. Study the effect of different E-C system configuration on the water productivity.
2. Design of the prototype focusing on the optimum size of Evaporation chamber and also the condenser in order to improve the efficiency of the evaporator and condenser.
3. Study the effects of the main parameters such as inlet water and air temperatures to the evaporator and wind speed on unit production.
4. Study the possible enhancement that can be achieved by using the packed column instead of open column as evaporator on the system productivity.
5. Study the possibility of using other heat sources such as cogeneration or geothermal sources and their integration with a solar system.
6. Support the installation of this type of desalination process especially in the sparsely population regions.

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