

RESEARCH ARTICLE

STUDY OF A NEW PASSIVE SOLAR DESALINATION DESIGN WITH A HEAT RECYCLING SYSTEM

Zeyad Ahmed Alsakkaf¹ , Gamal A. A. Al-Dahbali² and Adel A. M. Saeed^{3,*} ¹ Dept. of Chemistry, Faculty of Education University of Aden, Aden, Yemen; zeyadalsakkaf@gmail.com² Dept. of Chemistry, Faculty of Lawdar Education University of Abyan, Abyan, Yemen; gamal_cmc@yahoo.com³ Dept. of Chemistry, Faculty of Science, University of Aden, Aden, Yemen

*Corresponding author: Adel Ahmed Mohammed Saeed; E-mail: adel_saeed73@yahoo.com

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Abstract

This study presents a new and innovative suggestion to design a solar water desalination system by the direct passive method, with the aim of raising productivity by recycling the energy lost during the desalination process and raising the efficiency of condensation. In this study, the innovative design was evaluated to demonstrate its ability to increase the productivity of direct passive solar desalination while maintaining simplicity of installation and ease of operation. A prototype of the design was built to make a detailed study on the efficiency of the design and its ability to raise productivity under several different operational and climatic conditions in the city of Aden - Yemen, where several experiments were made to desalinate seawater taken from the city's coasts and the water of semi-salty wells in the city of Aden to compare the readings different. The results prove that the innovative design can raise productivity up to 80% higher than normal. The effect of pond water depth and salinity on productivity was studied. The results show that the higher the water depth in the evaporation basin, the higher the production capacity, and the higher the water salinity, the lower the production capacity of inactive direct solar desalination systems. This study also provides an assessment of the quality of the water produced by the innovative design by carrying out several chemical tests and making a comparison with the water quality before desalination to ensure that the design is capable of desalinating seawater or semi-salty well water to produce potable water. The results were confirmed for the quality of the produced water, which confirms the ability of the design to produce potable water in accordance with local and international standards, as the amount of total dissolved salts in sea water before desalination was 41340 mg/L and in well water 1300 mg/L, while after desalination by innovative design The total dissolved salts in treated sea water was 210 mg/L and in treated well water was 34 mg/L.

Keywords: Passive, Solar desalination, Productivity, Suggested design.

1. Introduction

Due to the continuous increase of the world population and industrial development, the demand for fresh drinkable water is increasing every year [1], where 40% of the world population cannot get clean drinkable water [2]. Therefore, creating a practical water desalination technology is a necessity to solve the drinking water shortage issue worldwide. Many water desalination methods were used during the last decades such as single-stage distillation, multi-stage flash, multi-effect boiling, vapor compression, freezing process and ion exchanging, all of these techniques require energy from different

sources such as fossil fuel, nuclear energy, and renewable energy.

The water desalination plants that use fossil fuel as energy source cause between 1.4 to 1.8 kg of CO₂, emitted to the atmosphere per cubic meter of produced freshwater, these water desalination plants have a usual capacity of 1 billion m³ every year [3], which means it is more harmful to the environment than using renewable energy. Solar energy is 42% of the renewable energy used for seawater desalination around the world [2]. Due to its availability, low cost, and simplicity.

1.1 Solar desalination

Solar energy has taken the scientists' interest for the last decades due to the low cost, continuity, availability and less environmental hazards. Solar energy can give us around 1.36 kw/m^2 in one sun [4], this value can vary during the year depending on the distance between the sun and the earth, this amount of energy can be used in different majors and applications such as electricity production and seawater desalination.

Solar desalination is a process of removing mineral salts and impurities from the saline water by using solar energy [5], which is one of the most important systems to treat seawater and groundwater to produce fresh drinkable water. Solar desalination systems have two main categories, direct and indirect solar desalination systems [6], depending on how the solar energy is used, either directly to evaporate the saline water or being collected indirectly by solar collector plates to produce electricity to be then used for either circulating the vapor or pumping and heating the saline water in many varied water desalination techniques.

Direct solar desalination systems are classified into two types, passive and active systems [7]. Active solar desalination systems require an external energy to enhance the desalination process, while the PSDS utilizes the solar energy only without any external source of energy. Passive solar desalination systems can produce drinking water of $2 - 4 \text{ L/m}^2/\text{day}$, while the active solar desalination systems can produce more than $36 \text{ L/m}^2/\text{day}$. Active solar desalination systems have a more complicated structure, high productivity and higher costs [1]. Passive solar desalination systems have a low initial cost for their simple construction and no external energy requirement [7]. Low fresh drinking water productivity is the main disadvantage of the passive solar desalination systems due to the amount of wasted energy during the process and low condensation efficiency [8]. Therefore, several modifications were suggested to improve the direct passive solar desalination systems' efficiency. This makes many of the last studies go toward improving and developing the passive solar desalination systems to increase the efficiency and the fresh drinking water productivity. Thereby there is a wide variety of direct passive and active solar desalination systems.

1.2 Passive solar desalination systems

Passive solar desalination system is a creative way to use the solar energy without using any external source of energy to produce freshwater using either basin or wick solar stills [6]. The main concept of the basin solar still as shown in Fig.1. is absorbing the solar energy directly, to evaporate the salty water located in a basin, which prefers to be isolated from the bottom for less energy loss and painted black from outside to absorb maximal solar energy [7]. This basin is covered by a transparent glass to

allow the solar energy to pass to the interfacial air inside the solar still and the water in the basin. This cover works as a condensation surface as well. The water in the basin is heated by the heat transferred conductively from the black basin walls and convectively from the interfacial air inside the solar still [9]. The water starts to evaporate as its temperature starts to rise, when the interfacial air inside the solar still gets saturated the condensation process begins on the glass cover. When the cover absorbs the energy from the saturated interfacial air during the condensation process its temperature increases, the absorbed energy will be transferred to the ambient windy air by convection, which means energy is wasted [6]. The loss of energy is the main reason why the direct passive solar desalination systems have low productivity. In addition, the difference in the temperature between the water surface inside the basin and the glass cover is impacting the condensation rate. The smaller the temperature difference is the more the condensation rate increases [9].

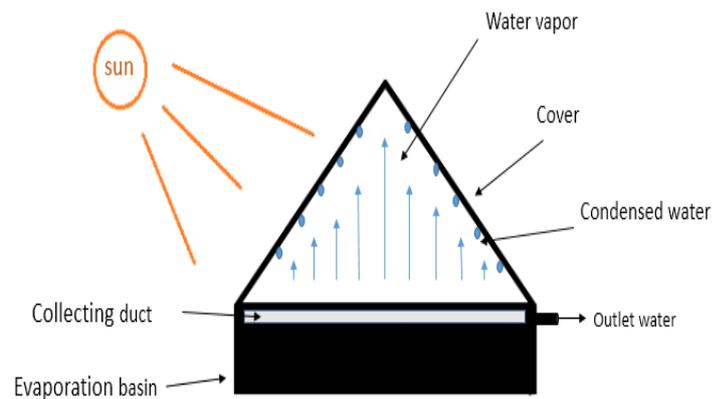


Fig. 1: Passive Solar Desalination Still Concept

1.3 Efficiency factors of passive solar desalination system

The type of passive solar desalination system design is one of the most effective factors in the productivity of the passive solar desalination systems. There are many types of designs of passive systems such as single slope or double slope, single basin stills, shape of the cover, multiple-effect stills, wick solar stills, and hybrid designs [10, 11]. Many other adjustments may affect the productivity of passive solar desalination systems such as fins, reflectors, stepped absorbers, and thermal storage materials [12-16].

Weather and operational conditions are also affecting the productivity of passive solar desalination systems including solar radiation, ambient temperature, wind velocity, water depth and water salinity [6, 9, 10].

1.4 Energy balance

The energy is wasted during the passive solar desalination process mostly due to the waste of energy from the cover into the ambient and the waste of energy from the basin bottom and walls, as shown in Fig.2. To calculate the amount of energy wasted by the cover we may use the following equations [17]:

$$q_{tl,co-amb} = q_{rd,co-amb} + q_{cn,co-amb} \quad (1)$$

$$q_{tl,co-amb} = q_{tl,bw-ci} + \alpha_c I(t)_{rs} \quad (2)$$

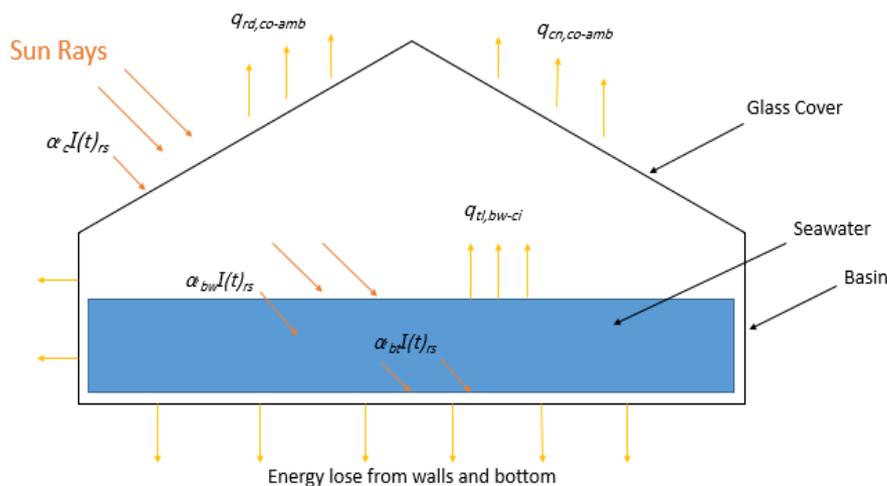


Fig. 2: Double slope passive solar system

1.5 New passive solar desalination system

The suggested passive solar still consists of one steel basin with a double slope cover, one side of the cover is made of transparent glass to allow the solar energy enters into the saline water located inside the steel basin and the second side of the cover is composed of two saline water-feeding tanks. The first tank works as a condensation surface absorbing the heat from the water vapor by convection and transferring the absorbed heat to the feeding saline water by conduction to be recycled in order to reduce the waste of energy, in addition, to maintain the condensation surface temperature continuously low. The

condensation rate increases by increasing the temperature difference between the saline water surface temperature and the condensation surface temperature. Therefore, the freshwater productivity will increase by continuously cooling down the condensation surface. The second saline water-feeding tank function is to utilize the covered solar area by the first shaded tank, absorbing the solar energy by the second tank outer surface and transfer it to the feeding saline water increases the total absorbed solar energy, as shown in Fig.3. The first feeding tank is thermally isolated to prevent any energy lacking from the second tank, which may lead to raise the condensation surface temperature.

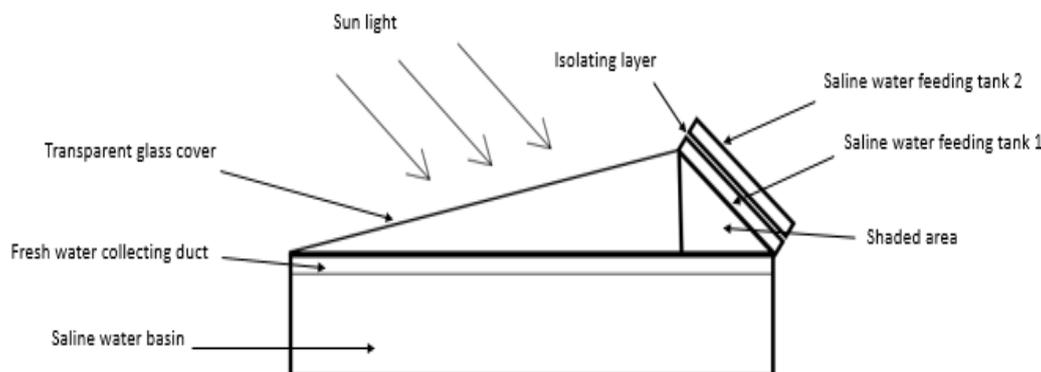


Fig. 3: Side section of the suggested design

2. Experimental Section

2.1 Prototype installing

The main body of the prototype was made of treated steel to resist corrosion and rust with a high thermal conductivity so it can transfer the solar energy to the water placed on the evaporation basin. The top cover was made of transparent glass to let the solar energy pass to the water placed on the evaporation basin in order to heat up the salty water as much as possible. The two feeding tanks were attached together by a thermal isolated layer, both of the feeding tanks were connected by thermal isolated pipes to let the feeding salty water flow into the evaporation basin, those pipes were attached by two valves to control the flow rate. A collecting duct was installed at the top of the evaporation basin, to collect the condensed fresh water. Fig.4. is showing the suggested design actual prototype.

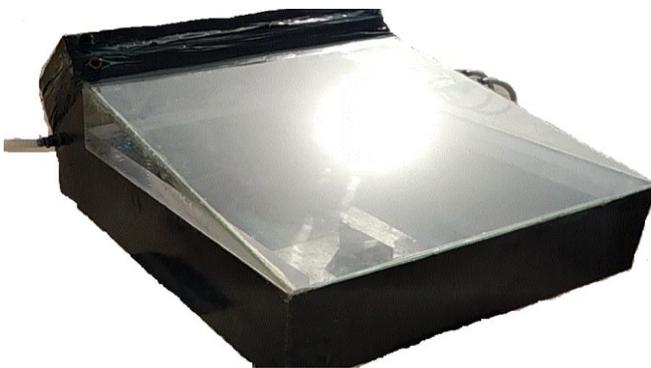


Fig. 4. Suggested passive solar desalination prototype

2.2 Costs analyzing

Due to the simplicity of the new suggested passive solar desalination design, the operational cost is almost zero and the capital costs are very low comparing with most of the recent passive solar desalination systems [18-20]. The prototype was installed based on 0.8 m² surface area of the basin, the capital costs are shown in Table1.

Table 1: Capital Cost Analysis.

Item	Cost, \$
Galvanized iron sheet	25
Glass	10
Thermal isolating sheet	5
Ball valves	5
Plastic duct	5
Feeding tubes	5
Painting and accessories	15
Welding works	10
Wood plate	2
Total	82

2.3 Investigations

This study aimed to evaluate the efficiency of the suggested passive solar desalination system by

investigating the productivity and evaluating the chemical parameters of the treated seawater and tap water samples. Therefore, when the prototype was ready a tap water samples were collected from Aden public tap water in August 2021. Seawater samples were collected also from Aden AL-Khissa coast, which has total dissolved salts TDS 40736 mg/L [21]. Both tap water and seawater samples were applied on the prototype to prepare a freshwater sample. Several experiments were performed to produce freshwater using the new suggested passive design. The produced freshwater samples were used to perform several chemical tests to evaluate the efficiency of the suggested passive solar desalination systems to produce drinkable water comparing with the local and international drinking water standards. Using the equipment and methods as shown in Table 2.

Table 2: Methods and equipment

Parameter	Symbols	Analytical method	Unit	Equipment
Acidity	PH	Electrometric	-	PH meter Thermo 420A+
Total dissolved salts	TDS	Electrometric	mg/L	Thermo Orion 150A+
Electrical conductivity	EC	Electrometric	μS/cm	Thermo Orion 150A+ UV
Iron Ions	Fe ⁺³	Photometric	mg/L	photometer HACH UV
Sulfate	SO ₄ ⁻²	Photometric	mg/L	photometer HACH UV
Nitrate	NO ₃ ⁻	Photometric	mg/L	photometer HACH UV

3. Results

3.1 Chemical tests results

The results of the chemical tests for the seawater and tap water samples before and after the treatment are represented in Table 3 and Fig.5.

Table 3: Water quality analyzing

Parameter	Seawater	Treated seawater	Tap water	Treated tap water	WHO Standards
PH	7.5	7.2	7.93	7.24	6.5 - 8
TDS (mg/L)	41340	210	1300	34	500
EC (μS/cm)	72400	386	2270	64	400
Fe ⁺³ (mg/L)	2.5	0.32	0.17	0.06	0.3
SO ₄ ⁻² (mg/L)	5120	10	2540	0.01	200
NO ₃ ⁻ (mg/L)	2.3	0.4	1.7	0.1	50

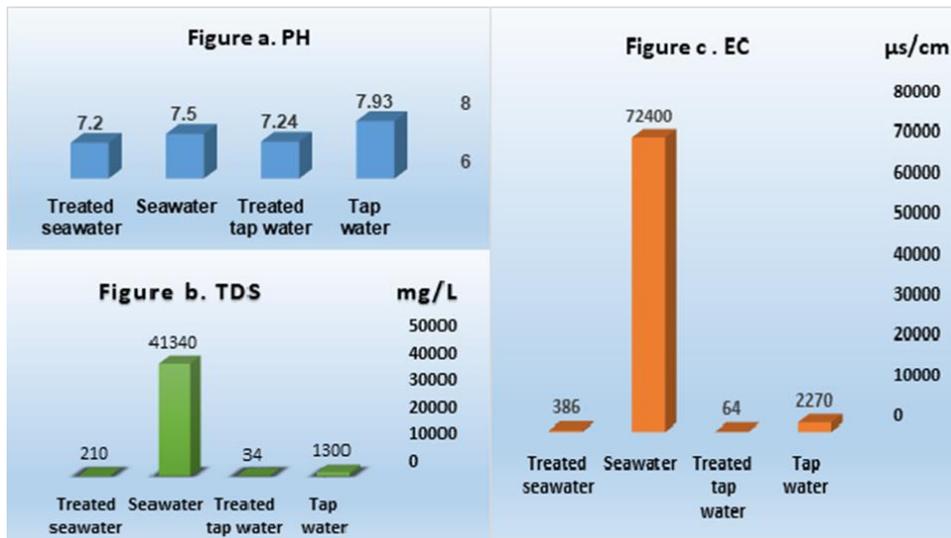


Fig. 5. Chemical tests comparison

3.2 Productivity investigations

The prototype productivity was examined in Aden city republic of Yemen during the period 2021/2022 at a variety of seasons and weather conditions, a several experiments were done without the feeding tanks to give the following results as shown in Table 4 below:

Table 4: Productivity comparison without the feeding tanks

Season	Ambient Temp. °C	Prod. L/m ² /day Exp.1	Prod. L/m ² /day Exp.2	Prod. L/m ² /day Exp.3	Mean
Summer	38	2.6	2.5	2.7	2.6
	36	2.5	2.4	2.5	2.4667
Winter	28	1.2	1.15	1.3	1.2167
	25	0.9	1.0	0.8	0.9

The prototype productivity was examined with the feeding tanks by several experiments at the same conditions, the results were given in Table 5:

Table 5: Productivity comparison with the feeding tanks

Season	Ambient Temp. °C	Prod. L/m ² Exp.1	Prod. L/m ² Exp.2	Prod. L/m ² Exp.3	Mean
Summer	38	4.5	4.7	4.8	4.667
	36	3.8	4.1	4.3	4.067
Winter	28	1.6	1.5	1.6	1.833
	25	1.5	1.4	1.4	1.433

The comparison between the productivity results after using the suggested feeding tanks to recycle the wasted energy, and the results of the productivity without using the suggested feeding tanks is shown in Fig.6.

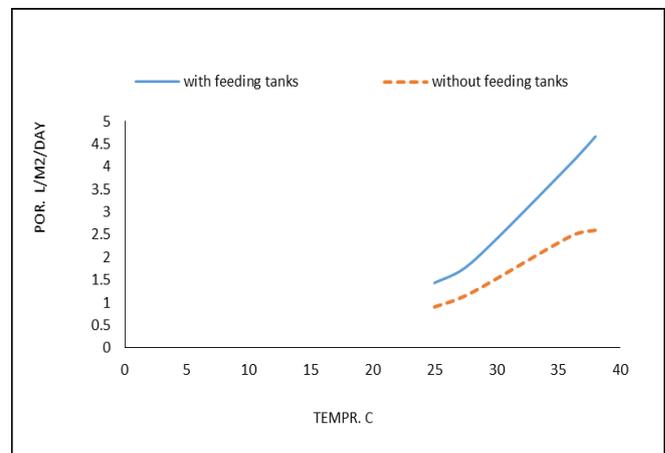


Fig. 6. Productivity comparison

3.3 Productivity factors investigations

The productivity is influenced by the basin water depth, the wind velocity and the saline water salinity. All are factors that can change the fresh drinking water productivity. The suggested passive solar desalination system achieved different productivities under different conditions and factors as shown in Table 6.

Table 6: Productivity factors

Experiment	Water depth, cm	Ambient Temp. °C	Treated Tap water Prod. L/m ² /day	Treated Seawater Prod. L/m ² /day
Exp1	3	38	4.8	3.9
Exp2	4	38	4.6	3.5
Exp3	5	38	4.2	3.1

The effect of the water depth and salinity factors is shown in Fig.7.

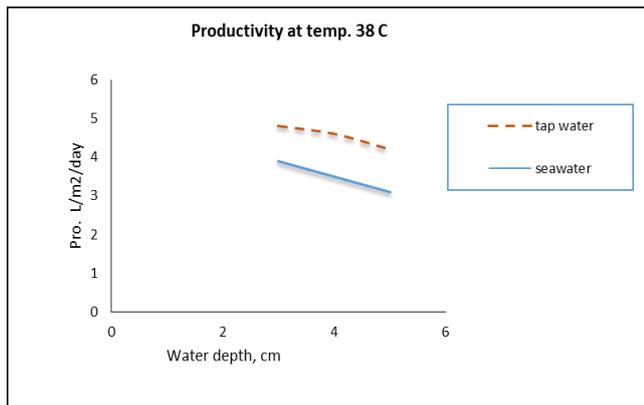


Fig. 7. Productivity factors

4. Discussion

4.1 Water quality tests

The total dissolved salts TDS was very high in the seawater with 42340 mg/L it is more than thirty times than it should be according to local and international standards for drinking water, but after it has been treated by the suggested system it decreased 99.5% from 42340 mg/L to 210 mg/L, which is good for drinking water. TDS was found in tap water samples 1300 mg/L, which is higher than the WHO standards of TDS for drinking water in the local standards, this value has decreased after the treatment 97.4% from 1300 mg/L to 34 mg/L, which is typical for drinking water according to international standards. Seawater samples had very high electrical conductivity with 72400 $\mu\text{S}/\text{cm}$, which is much more than the local standard, which is maximum of 650 $\mu\text{S}/\text{cm}$, this value has decreased after the treatment 99.5% from 72400 $\mu\text{S}/\text{cm}$ to 386 $\mu\text{S}/\text{cm}$, which is in the normal range. The tested tap water had high electrical conductivity with 2270 $\mu\text{S}/\text{cm}$, which is more than three times higher than the maximum local standard, this value decreased after the treatment 97.2% from 2270 $\mu\text{S}/\text{cm}$ to 64 $\mu\text{S}/\text{cm}$, which is in the normal range according to the local and international standards. As we can see in Table 1, the SO_4^{2-} , NO_3^- , and Fe^{+3} ions levels were higher than they should be in both the seawater and the tap water, after the treatment they became between the normal levels for drinking water.

4.2 Productivity investigation

The suggested PSDS is capable to increase the fresh drinking water productivity 80% from 2.6 L/m²/day to 4.667 L/m²/day, during the summer of Aden city, and 60% from 0.9 L/m²/day to 1.433 L/m²/day, during the winter of Aden city. Using the feeding tanks during the desalination process makes the productivity increases in all of the applied experiments with lower cost and simpler construction comparing with recent passive solar desalination systems [22-24]. The productivity is higher than what Chiavazzo's *et al.* design had achieved [8]. The produced water by the suggested system is matching the

local criteria of drinking water. The ambient temperature is influencing the fresh drinking water productivity. As the ambient temperature increases as the productivity of the freshwater increases.

The water depth in the basin is influencing the fresh drinking water productivity, the smaller the water depth is the higher the freshwater productivity gets.

The salinity of the saline water is influencing the fresh drinking water productivity, the lower the salinity is the higher the freshwater productivity gets.

Conclusion

A new suggested passive solar desalination system was designed to increase the fresh drinking water productivity of the passive solar desalination systems, by recycling part of the waste energy and enhancing the condensation process .

A prove of point prototype was constructed to prove the suggested design ability to increase the PSDS productivity and to produce drinking water with high quality.

Several experiments were performed in Aden city, using the suggested passive solar desalination system prototype to investigate the efficiency and the productivity in different conditions.

When the suggested passive solar desalination design was used with the two suggested saline water-feeding tanks, the mean of the freshwater productivity was increased to 4.667 L/m²/day, during the summer of Aden city at 38 °C, while the mean of the freshwater productivity was 2.6 L/m²/day, at the same conditions without using the suggested feeding tanks. Which means an 80% increase of the fresh drinking water productivity .

The new suggested passive solar desalination system by this paper is the optimal design for seawater desalination in the area of the study which suffering of poor resources. The new suggested passive solar desalination system design is more suitable to be used in the area of the study than most of the recent designs due to the structural simplicity of the new suggested passive solar system, low costs and high relative productivity.

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Author information

ORCID 

Zeyad Ahmed Alsakkaf: [0000-0001-8868-1784](https://orcid.org/0000-0001-8868-1784)

Adel A. M. Saeed: [0000-0002-1154-2994](https://orcid.org/0000-0002-1154-2994)

مقالة بحثية

دراسة تصميم مقترح لنظام تحلية المياه بالطاقة الشمسية بالطريقة المباشرة مع نظام إعادة تدوير الطاقة المفقودة

زياد أحمد عبدالله السقاف¹، جمال أحمد عبدالله الدهلي² و عادل أحمد محمد سعيد³ * 

¹ قسم الكيمياء، كلية التربية عدن، جامعة عدن، عدن، اليمن

² قسم الكيمياء، كلية التربية لودر، جامعة أبين، أبين، اليمن

³ قسم الكيمياء، كلية العلوم، جامعة عدن، عدن، اليمن

* الباحث الممثل: عادل أحمد محمد سعيد؛ البريد الإلكتروني: adel_saeed73@yahoo.com

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المُلخَص

تقدم هذه الدراسة مقترحاً جديداً ومبتكراً لتصميم نظام تحلية المياه بالطاقة الشمسية بالطريقة المباشرة غير النشطة بهدف رفع الإنتاجية عن طريق إعادة تدوير الطاقة المفقودة أثناء عملية التحلية ورفع كفاءة التكييف. في هذه الدراسة تم تقييم التصميم المبتكر لإثبات قدرته على رفع إنتاجية التحلية الشمسية المباشرة غير النشطة مع الحفاظ على بساطة التركيب وسهولة التشغيل. تم بناء نموذج من التصميم لعمل دراسة تفصيلية حول كفاءة التصميم وقدرته على رفع الإنتاجية عند ظروف تشغيلية ومناخية مختلفة في مدينة عدن-اليمن، حيث تم عمل تجارب عديدة لتحلية مياه البحر مأخوذة من سواحل المدينة ومياه الآبار شبه المالحة في مدينة عدن لعمل مقارنة بين القراءات المختلفة. أثبتت النتائج قدرة التصميم المبتكر على رفع الإنتاجية إلى 80% أعلى من المعتاد. دُرس تأثير عمق الماء في الحوض وملوحته على الإنتاجية. تبين من النتائج أنه كلما زاد عمق الماء في حوض التبخير ارتفعت القدرة الإنتاجية، وكلما ارتفعت درجة ملوحة الماء انخفضت القدرة الإنتاجية لأنظمة التحلية الشمسية المباشرة غير النشطة.

تقدم هذه الدراسة أيضاً تقييماً لجودة الماء المنتج من التصميم المبتكر وذلك عبر تنفيذ عدة فحوصات كيميائية وعمل مقارنة مع جودة الماء قبل التحلية للتأكد من أن التصميم قادر على تحلية مياه البحر أو مياه الآبار شبه المالحة لإنتاج مياه صالحة للشرب. وكانت النتائج مؤكدة لجودة الماء المنتج مما يثبت قدرة التصميم على إنتاج مياه صالحة للشرب وفقاً للمعايير المحلية والدولية، حيث أن مقدار الأملاح الذائبة الكلية في مياه البحر قبل التحلية كانت 41340 ملليجرام/لتر وفي مياه الآبار 1300 ملليجرام/لتر، أما بعد التحلية بواسطة التصميم فقد كانت الأملاح الذائبة الكلية في مياه البحر المعالجة 210 ملليجرام/لتر وفي مياه الآبار المعالجة 34 ملليجرام/لتر.

الكلمات المفتاحية: التحلية الشمسية المباشرة، غير النشطة، الإنتاجية، تصميم مقترح.

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