Mechanical Modeling of a High-Performance Solar Desalination System Based on a Three-Step Approach

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ABSTRACT: *Solar desalination systems are a kind of water purification system that can be utilized in dry regions. However, the low efficiency and performance of these systems are some of the main challenges of these mechanisms that affected their development. So, In this paper, a novel modified model is presented for increasing the efficiency and performance of these systems. This suggested modification is based on a triple action. The first of these actions includes discovering the optimal location for the installation of the solar still water. Increasing the contact surface of the water spraying and keeping the saltwater in wide solar still is a second approach for increasing the evaporation of water. In the end, a modern condensing system based on an innovative fog (water particle) trapper/harvester. This system includes fog fences, a cool water pipe loop based on the outdoor temperature, and forced-controlled airflow. Therefore, based on this method, a conceptual design of the solar still water is modeled For UAE. The results of this study show that the modified solar still can make 3.94 L/m^2 per day. The cost per liter of each liter of water is 0.0344 \$. These results show that the efficiency of the proposed model is two times higher than the traditional method with the same cost. Also, these results are in an acceptable range in comparison with the newly modified models presented by researchers.*

KEYWORDS: *Desalination; Modified system; Three-step approach; Solar still; Fog fences.*

INTRODUCTION

Water has an important role all around the world. Naturally available freshwater reserves are not capable of meeting freshwater demands[1,2]. Only 0.5% of the 1.4 billion cubic kilometers of water in the world is accessible fresh water, which is furthermore poorly distributed across the globe [3]. The importance of this aspect is highlighted for Countries affected by water scarcity. United Arab Emirates (UAE) is affected by this scarcity. This country is located in a hyper-arid zone with very low precipitation and a high evaporation rate [4].

Desalination technology can tackle this problem[2].

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In this regard, Desalination of seawater is becoming an increasingly important means to address the scarcity of fresh-water resources in the world [5–7]. Desalination is based on the removal of salts and minerals from water[7]. Because of the potentially unlimited availability of seawater, people have made great efforts to try to develop feasible and cheap desalting technologies for converting salty water to fresh-water [8–11].

The Conventional methods of desalination consume a huge amount of energy. The process of this method works on the heating and then cooling to drive the condensation of freshwater [4,12–14]. This process is required a huge amount of fossil fuel as Non-renewable Energy [15–17]. Nearly, 10,000 tons of oil are required every year to produce 1,000 m^3/day of desalinated water [18,19]. This has forced researchers to look for an alternate way of powering desalination units by renewable energy [20–23]. Thus, modern desalination technologies are developed[13,24–28]. The most important of these techniques use solar energy for large-scale seawater desalination. These modern systems require thermal or electrical input that can be provided with solar energy [2].

The most important negative factor that affected the performance of this system was the expensive price of indirect solar energy[29–33]. For solving the problem, direct solar energy is represented in many systems [29–34]. Direct-Solar desalination is an effective way of converting solar energy to heat, directly, for seawater purification [35]. In these systems, direct solar energy is used for the evaporation of water. Vaporization drove by solar energy [36]. But, for condensing water, most of the efficient systems used external energy [31–33]. In some systems, natural condensers were used so that efficiency and the amount of water production are extremely low. Also, humidity is an important factor. Because Saturation of the air, seawater desalting in Coastal areas has a Low efficiency [29,30,37]. Therefore, on one hand, a solar still water system is costly by using external energy for condensing water and on the other hand, has low efficiency by using natural condensing.

So in this paper, based on a novel conceptual design, a new technique is presented for covering the cited problems of desalinating. In the first, such as the new researches(references [20,29,30]), direct solar energy were used to evaporation, also in parallel of this method, by increasing the temperature and surface of evaporation and also by sparing the saltwater, the amount of vapor is increased. Furthermore, in facing with low efficiency problem, an innovative method, based on water trapper/harvester, is introduced for increasing the efficiently of water condensing. Also, for improving the performance, this desalination system must be installed in a dry place and far from the water source (sea). In the next, evaluation of the amount of the required energy is considered. In the final step, for estimation the efficiency of the system, several estimation and comparison are presented in field of energy and economic aspects.

EXPERIMENTAL SECTION

In this section the phases of modeling the high-performance desalination system is presented step by step. In Fig. 1 the flowchart of modeling is shown.

Selection the target location- geographical and climate aspects

United Arab Emirates has a desert climate with high temperatures, especially in spring and summer [38]. The south of the country, in the emirate of Abu Dhabi and also AlAin, is almost uninhabited. Here, the climate is similar to the coast, and it's even hotter in summer, but the air is drier because of the greater distance from the sea [39] . So, because of poor humidity, these places are suitable for the vaporization of the water. Since dry air has a massive capacity for moisture absorption. This capacity and plenty of sunlight cause that the evaporation systems such as solar desalination has a good chance to install in these places.

In these locations, summer is very hot and sunny, with daytime temperatures ranging from 38 °C to 42 °C between May and September with 20 Tera-joule, Average daily total solar radiation. April and October are also hot months, with highs around 33/36 °C. During the hottest days, the temperature can reach 47/48 °C [39]. During these months, the average sunshine hours per day is 10 hours[39]. The average relative humidity for this month is about 30% an average atmospheric pressure of 1.005 Bar. The elevation from the sea is about 50-180 m and the vertical distance from the sea is about 100 km. All of this information is listed in Table 1. In Fig. 2, a map of the locations is shown.

Table 1: geographical and climate aspects of selected locations-spring and summer [38,39]

location	Ave. daily temp. (ºC)	sunshine hours per day(h)	Ave. related humidity (%)	Elevation(m)	Distance from sea (km)	Ave. atm. Pressure (Bar)	Ave. daily solar radiation(TJ)
South of Abu Dhabi	35	10	30	100	100	1.005	20
Al Ain	35	10	30	180	100	1.005	20

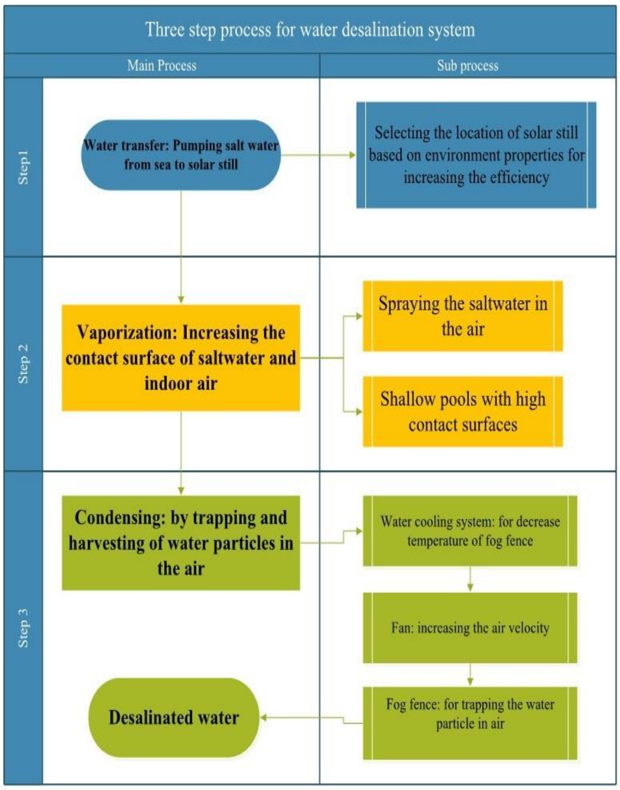


Fig. 1: The flowchart of modeling the high-performance desalination system

Simulation of the model and desalination process

In this section, a simulation of the model is presented. The modified desalination system consists of the saltwater pipeline, solar panels for supplying the pumping energy, solar still including evaporation and condensing systems (Harvesting and trapping the pure water).

Saltwater Pipeline, pumping system and solar panels

The saltwater pipeline is an isolated and underground infrastructure that provides water for desalination. Because of the elevation from the sea, a mechanical pump is needed. The pipe diameter is 280 mm (Poly Ethylene Pipes), based on the capacity of water desalination The energy of the pump is generated by the solar panels during the desalination process. The average energy for pumping water is extracted from Equation 1[40].

Fig. 2: map of the location

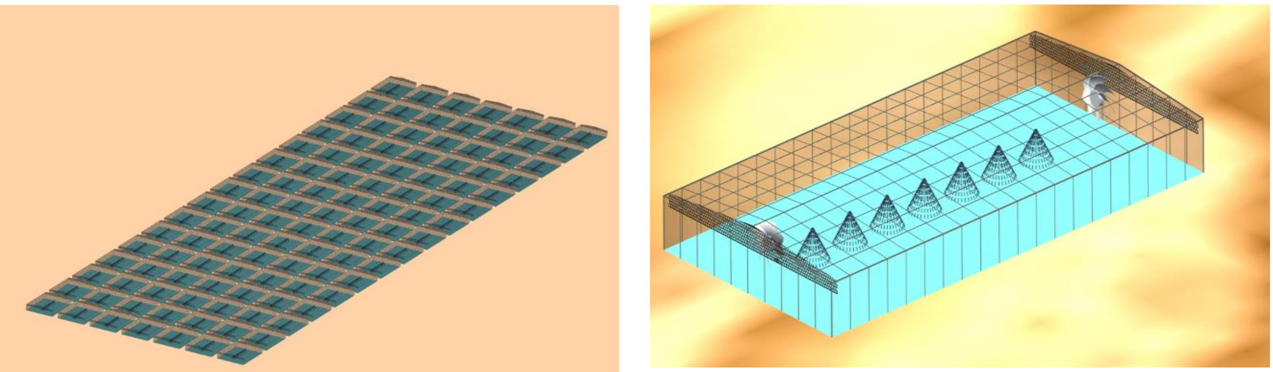
$$E = mg\left(h_L + h_p + h_f\right)$$
$$h_L = 100\,, h_p = 50\,, h_f = \left(f\frac{L}{D} + K_C + K_V\right)\frac{v^2}{2g} \qquad (1)$$
$$f = function(Re, \frac{\varepsilon}{D})$$
$$Re = \frac{\rho v D}{\mu}$$

Where E is the pumping energy, m is the total water mass, g is gravitational acceleration, h_L is the physical change in elevation between the sea level and the receiving location, h_p is the spray pressure in the solar salons, h_f is illustrated to head loss, f *is* the Darcy friction factor, L is the length of pipeline, D is the diameter of the pipe, k_C is resistance coefficient due to couplings, k_C is resistance coefficient due to valves, v is water velocity, Re is Reynold's number, ε is Surface roughness of pipe and μ is kinematic viscosity of water [40].
The parameter h_f is also can be written as Equation 2:

$$h_f = \left(f\frac{8L}{D^5\pi^2}\right)\frac{Q^2}{g} \qquad (2)$$

Where Q is the volumetric flow rate in the pipeline. the relationship between friction, turbulence, and roughness in pressurized flows is the Colebrook–White equation (Equation 3) [41]:

$$\frac{1}{\sqrt{f}} + 2log_{10}\left(\frac{\varepsilon}{3.7} + \frac{2.51}{Re\sqrt{f}}\right) = 0 \qquad (3)$$
$$f = \frac{D^5\pi^2 h_f}{8LQ^2}$$



A: Solar stills plant B: A solar still unit

Fig. 3: Solar still

Also f ,with the idea of the general nonlinear function, known as the Swamee equation, is given by Equation 4 [42]:

$$\left(\left(\frac{64}{Re}\right)^{8}+9.5\left(\ln\left(\frac{\varepsilon}{3.7D}+\frac{5.74}{Re^{0.9}}\right)-\left(\frac{2500}{Re}\right)^{6}\right)^{-16}\right)^{0.125} \qquad (4)$$

Evaporation system

In this section, the water evaporation procedure is discussed. The Evaporation of water is in the process into 90 isolated solar still (Fig. 3). All of these solar stills have the maximum effort from the sun's energy. The roof and body of these solar stills are made with polycarbonate sheet that has well efficiency in absorption and storing the sun's energy in the solar stills. This ability cause rising in interior temperature of solar stills. The enormous energy of sunlight can turn the solar stills into a scorching oven. The inside temperature can rise over 75º during the day time. This increase is because of the sunlight and greenhouse effects of solar stills [43–45]. The average estimated temperature, during a day, is 65º through the evaporation of water in a day[45,46]. This hot air has a good capacity for absorbing vapor (Table 2).

For increasing the amount of evaporating in hot indoor air, at the first step the temperature of inlet saltwater raised by cycling this water in the solar still salon .at the second step, the warm water, sprayed to the air. The spraying mechanism has consisted of several parallels distributers that works mechanically with 5 bar water power (Fig. 4). This action rises the surface of water immediately and the percentage of moisture is mainly increased. This process is continued until the air is saturated. The parallel of these two actions, the saltwater pool in the solar salons has a good influence on increasing the water percentage in the air.

Table 2: Maximum moisture carrying capacity of air[47–49]

Temperature (ºC)	Maximum Water Content (g/m^3)
40	51
50	82.8
60	130
70	197
80	291
90	418.6

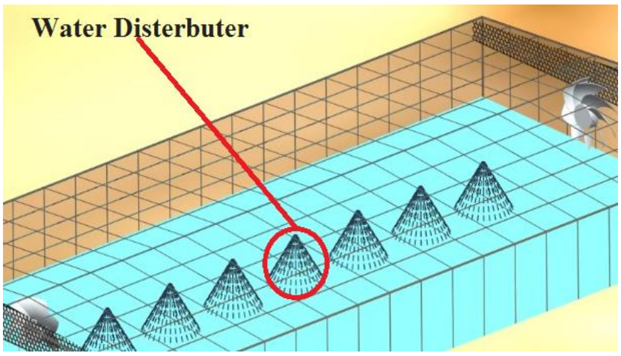


Fig. 4: Water distributions system

Droplet heat transfer

Whenever a water droplet confronts with an unsaturated airflow, heat and mass transfer happens [50]. The energy balance over a droplet in contact with an airflow can be expressed as:

$$m_{sw}C_w\frac{dT_d}{dt}=h_c s_d(T_a-T_d)-\frac{dm_d}{dt}h_{fg} \qquad (5)$$

$$\frac{dm_d}{dt}=h_d s_d(\rho_{s,int}-\rho_{evw}) \qquad (6)$$

→ mass reduction rate of water droplet because of evaporation

The left hand side of Equation 5 indicates the internal energy variation rate of the droplet and the right hand side includes airflow and the particle convection heat transfer rate and the droplet evaporation rate. In this equation m_{sw} is the water content in air of salons, C_w is heat capacity of water, h_c is the heat transfer coefficient, h_d is mass transfer coefficient, s_d is the Source term of droplet mass, T_a is the air temperature and T_d is droplet temperature. In Eq. (6) where $\rho_{s,int}$ is the saturated vapor – air layer density and ρ_{evw} is the vapor density. Equation 5 and Equation 6 indicated that there is latent heat transfer because of droplet evaporation and sensible heat transfer caused by convection and radiation. Convection and radiation heat transfer methods are negligible in comparison to the latent heat transfer caused by evaporation [51]. So, in the following, the calculation of the energy is investigated in Eq. (7):

$$SL_E = 5.75\ \frac{kwh}{day.m^2} \quad A = 10^6\ m^2$$
$$E_S = SL_E\ .A = 20.7 * 10^{12}\ j \qquad (7)$$
$$m_{Sw} = 64 * 10^6\ kg$$
$$Q_{Ev} = m_{Sw}\ C_w \Delta T + m_{Sw} L_{evw} = 2.15 * 10^{12}\ j$$
$$\longrightarrow E_S \simeq 8\ Q_{Ev}$$

In Equation 7, SL_E is the solar energy in target location, A is area of the solar stills, E_s is the total solar energy of all solar stills, Q_{Ev} is the energy for evaporation of water, ΔT is the change of water temperature, L_{evw} illustrated to the latent Heat of vaporization. Equation 5 shows that the solar energy in target location can evaporate the water 5-8 time in a day. Note that the efficiency of the system increased by spraying the water. The result of reference [50] shows that the spry system can increase the efficiency near 300%. The efficiency of a spray system is determined as the ratio of the real air temperature drop to the maximum probable air temperature drop [50]. It can be obtained from Eq. (8):

$$\tilde{\eta} = \frac{T_{air\ salon} - T_{Air\ Out}}{T_{air\ salon} - T_{Wet-bulb}} \qquad (8)$$

Harvesting and trapping the pure water

In a novel process, unlike the previous method, the condensing of water is occurred by a semi natural process. In this approach, fog fences are utilized for trapping the water drops. Also, the efficiency and performance of the systems are increased by crossing the intake saltwater loop pipe into fog fences. Finally, a fan by a controlled forced flow helps the fences to harvest the humidity from the air. This mechanism is installed at the top of the salon with a minimum of sunlight effect.

RESULTS AND DISCUSSION

In this section, the step by step discussions about the different parts of the proposed desalinating method is presented.

Head loss and pumping energy

In the first step, based on previous sections, the head Loss of pipeline is investigated. Nondimentional head loss of straight pipe is plotted in Fig. 6. The head losses are based on different roughness, the velocity of water and several diameters of pipes. In Fig. 6, the head Losses are nondimentional based on the head loss value of (roughness=0.003 mm, velocity=1 m/s and diameter=1000 mm).

Based on the equation, Moody chart and Fig. 5, the energy for piping the water can be calculated. Based on these calculations, the roughness=0.003 mm, velocity=3 m/s and diameter=250 mm is selected as the target. So, the required energy for daily usage of desalination is about 2 MW [52–54]. This amount of energy is generated by the solar power plants, (on a $4*10^4$ m^2 land). Verification of the calculation is shown in Fig. 7.

Performance discussions of the modified desalination method

Performance of the evaporation system

The evaporation systems prepared the saturated air for desalinating. By the Severe sunlight in the spring and summer, the evaporating system can saturate the water five times a day. 65º is the average interior temperature of the solar still that is considered based on section 2-2-2. The average air capacity of all solar warehouses is about 5 million cubic meters. In each cubic meter, there is about 160 gram of water drops (section 2-2-4). So in each period of system operation, 800 tons of water is desalted. in spring and summer, about 720 million liters of water can be purified. If this procedure is used for fall and winter with 25% efficiency, the Total amount of water reaches to 900 million liters in a year. A comprehensive comparison is presented based on the result of a review paper by *Katekar*

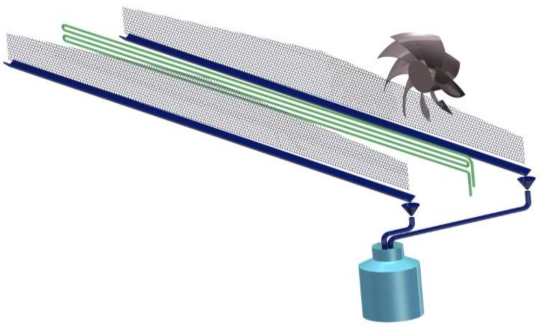


Fig. 5: Mechanism of water harvesting and trapping

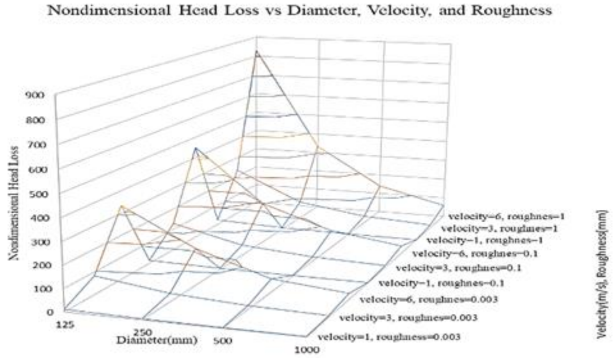


Fig. 6: Nondimensional Head Loss vs Diameter, velocity and roughness

and *Deshmukh* [55]. In this comparison, the new and high-performance desalination systems are considered (Fig. 8).

Performance of the trapping/harvesting of water particles mechanism

In the proposed modern conducting system, mainly, Fog fences are utilized for trapping and harvesting water particles in the air(fog). This trapping system consisted of fog fences, a cool saltwater loop pipe, and a controlled forced air flow the air flow is controlled by a mechanical fan. This fan is used to increase the contact of vapor particles by fog fences to speed up the trapping. The volume of solar stills is 5* 10^6 m^3. 1300 fan with 2340 Cfm needed for the circulation of air in salons for 2 times in an hour. The required energy for this process is 300-400 kW in 10-12 hours. This energy is supplied by the solar power plant.

The minimum capacity of one square meter of the Fog fences is about 10 liters of water in each process [56,57]. So, for 800 tons water, about 8 million square meters is needed. This area is located in top of lateral side of each warehouse, in two parallel lines.

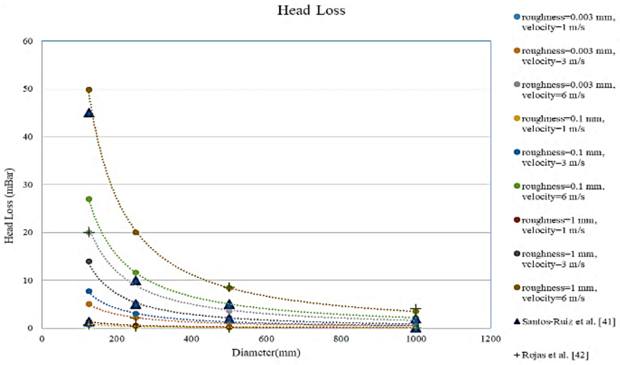


Fig. 7: Head Loss vs Diameter, velocity and roughness

Performance of pumping system solar power plant

Based on the range of water purification, it is shown that a minimum of 800 liters of saltwater is needed for the desalinating system. This saltwater must bring from the sea. Sea is far from the purification location and in a low elevation. So, the pumping system is utilized for the intake water. The energy of the pumping system is about 2 MW which is supplied by a solar power plant.

Determining the solar panel output per square meter depends on various factors. These include the size of solar panels, their position of installment and their numbers. For a general calculation the input rate for a solar panel is about 1000 watts per square meter. Most of the available solar panels work on 5-15 percent efficiently [52–54]. So, by this calculation, it can be said that solar panel output per square meter is approximately 50 watts. So, the maximum area of the power plant for supplying this amount of the energy is about 40000 m^2. The other required energy such as electrical fans are supplied by this power plan.so the total area is about 50000 square meters.

Economical discussions

In this section, by a commercial approach, the economical investigation and feasibility of the modified desalination method is presented. Based on the previous sections, the product of pure water is about 900 million liters in a year. According to the pet water fee in UAE, the total price of this amount of water is about 27 million United State dollars in a year. In contrast, the construction of the pipeline and pumping system, the solar power plant, construction and equipping of the solar stills mechanism must be calculated and added to the costs. Subsequently, For the pipeline and pumping system, based on the price of PE (Poly Ethylene) pipe, elastomer Insulation, and

Table 3: The costs of project

Approximate prices and costs-USD	
Solar power plant	2, 500,000
warehouses	20,000,000
Water trapping/harvesting	7,000,000
Electric fans and other instrument and part	200,000
Operation per year	300,000
Maintenance per year	1,500,000

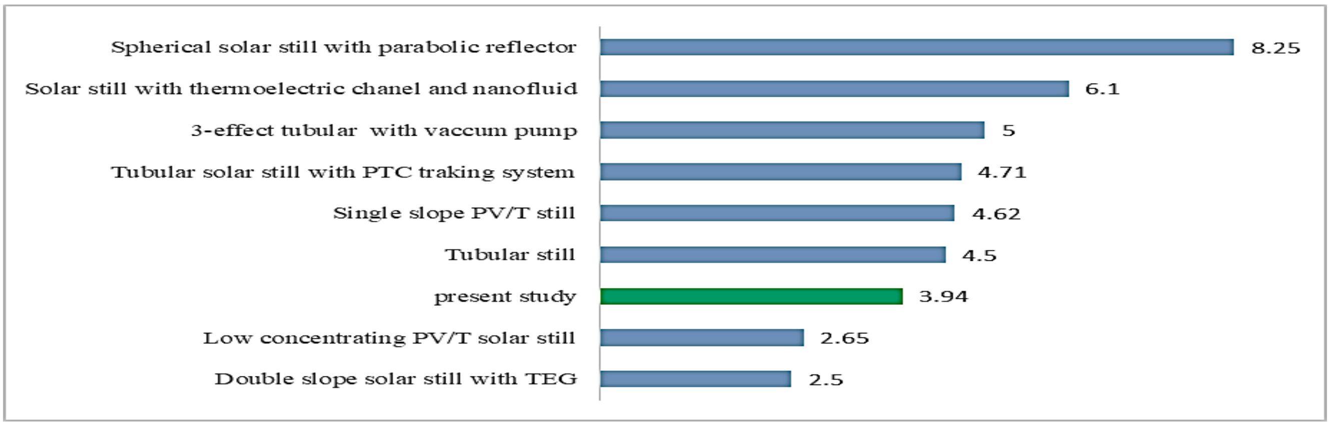


Fig. 8: Comparison of present study and other new and high performance solar stills based on their productivity (L/m² per day) [55]

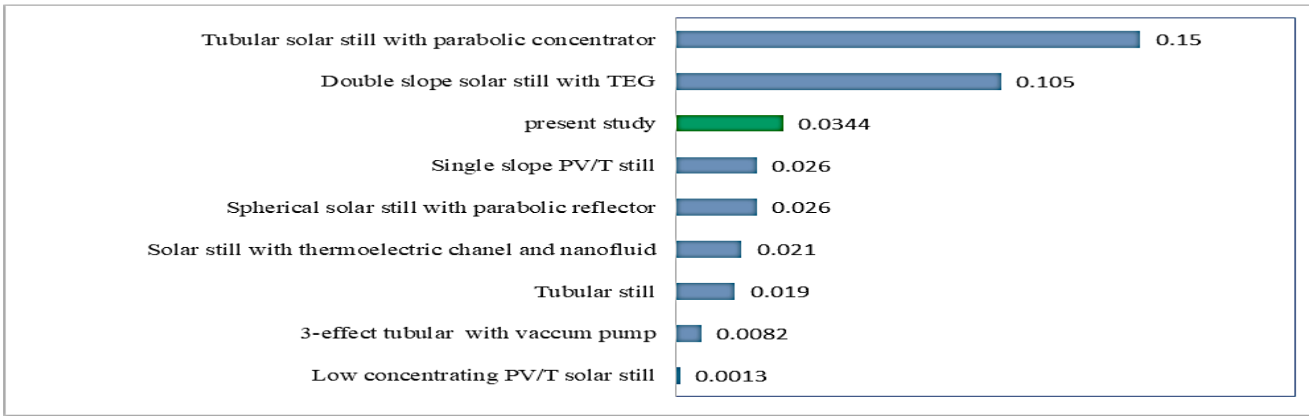


Fig. 9: Comparison of cost per liter for present study and other new high performance solar stills ($) [55]

pumping system, the costs are about 1 million dollars [58]. Also the price of solar power plant system is about 3 million dollars [58].For the warehouses, the cost of steel structure, drain and exhaust system of waste saltwater, storage of pure water, water distributes, poly carbonate plates, sealing of the roofs and walls and other processes is about 20 million dollars [58].For the water harvesting mechanism, the price of fences, cooling pipeline and air fans is about 7 million dollars [58]. Electric fans and other instruments and parts need 200,000 dollars. Operation and maintenance is 1,800,000 dollar per year. Note that this system is located in the desert. so the price of location is ignored. All of these costs are shown in table 3.

In next, based on the evaluations of this study, a comparison between this present model and some of the new and high performance systems([55]) based on the cost per liter of water is shown in Fig. 9.

The Payback period time is one on important factors of installation of solar stills. In the following, a comparison between some new high performance desalination systems([59,60]) and the present study is shown in Fig. 10.

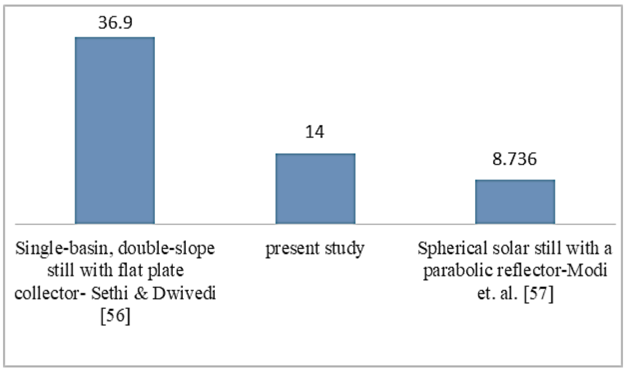


Fig. 10: Payback period (months) for high performance desalination systems[59,60]

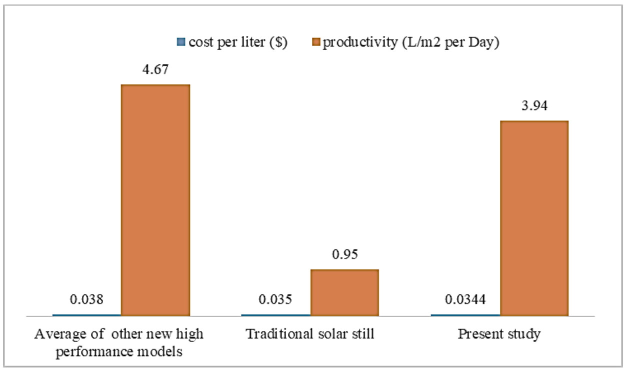


Fig. 11: a comparison based on productivity and cost per liter between traditional desalination methods, the average of new high performance systems and presented study [55]

Finally, a comparison based on productivity and cost per liter between traditional desalination methods, the average of new high performance systems, and the presented study are shown in Fig. 11 [55].

CONCOLUTIONS

In this study, a novel modified method, according to a conceptual design is presented for improving the solar desalinating systems. This modification is based on a triple action that is utilized for increasing the efficiency of the system.

Firstly, to increase efficiency and performance, the solar still is placed in a hot dry location far from the sea. In this study, the southern area of Abu Dhabi and AL Alin have suggested places in UAE for the construction of solar stills. These places are far from the sea with high temperatures and low humidity.

Secondly, by increasing the contact surface of saltwater and indoor air, the mechanism of vaporization is mostly increased. This mechanism consists of two different parts: spraying the saltwater in the air and using Shallow pools with high contact surfaces.

Finally for the third act, by using a modern technique, based on the trapping and harvesting of water particles in the air, condensing of water is accelerated and increased. This trapping system consisted of fog fences, a cool saltwater loop pipe with outdoor temperature (30º-40º) and a controlled forced air flow. The air flow is controlled by a mechanical fan. This fan is used to increase the contact of vapor particles by fog fences in order to speed up the trapping. The volume of solar stills is $5* 10^6$ m^3. 1300 fan 2340 Cfm needed for the circulation of air in salons for 2 times in an hour.

The proposed method is utilized in a conceptual design for a 1 million square meters solar still. This study is utilized for dry places of UAE. The calculations and investigations of the design show that proposed system can make 9 00 million liter water in a year. The calculations and analyses show that the productivity rate of the proposed model is higher than many new and high-performance systems that were presented by other researchers. Also, the cost investigation shows that the cost of per liter water is 0.034 $. The comparison of this cost with other models shows that this high-performance model is in the economic range. The most important factor in the installation of a desalination system is the payback period. The payback period of this system is 14 months. Because of the importance of water in UAE, the result indicated that this system can is an efficient role in this location. Also, the comparison of the present study by other new systems shows this efficiency.

In the consequent investigation, a comparison between the proposed model, the traditional model, and the average of other new high-performance systems is evaluated. This comparison shows that the efficiency of the proposed model is 2 times higher than the traditional method by the same cost. This evaluation state that the cost and the rate of desalination /productivity of this model are near to the average of new high-performance models.

In the end, the result study shows that the proposed model can play an effective role in facing the water crisis in the mentioned area and similar regions.

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