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Cost Analysis of Different Solar Still Configurations
التحليل الاقتصادى للاشكال المختلفة للمقطرات الشمسية

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الملخص

تحسين الانتاجيه لأى نظام اعذاب مياه باستخدام المقطر الشمسى يعتمد فى الاساس على التصميم. من أجل ذلك تناولت الدراسه تأثير الأشكال المختلفه للمقطر الشمسى. زيادة انتاجية المقطر الشمسى مع زيادة سعره الابتدائى قد تؤدى الى زيادة متوسط السعر السنوى للمنتج. من اجل ذلك يقدم هذا البحث تحليل اقتصادى لاغلب انواع المقطرات الشمسيه المستخدمه بهدف الوصول للمقطر الاقتصادي. أشتمل البحث على دراسة 17 تصميما مختلفا للمقطرات عالية الانتاجية والمنخفضة الانتاجيه. وقد اوضحت الدراسه ان المقطر الشمسى الاحادى الميل وكذلك الشكل الهرمى يعطى افضل انتاجيه يوميه. الشكل الهرمى يعطى حوالى 1533 لتر لكل متر مربع وينخفض بحوالى 250 لتر/متر المربع فى حالة استخدام نظام شمسى دوار. اقل تكاليف انتاجيه وجدت من الشكل الهرمى وهى 0.0756 LE/l (حوالى 0.0135 $/l) بينما عند استخدام نظام شمسى دوار كانت القيمة وهى 1.288 LE/l (حوالى 0.23 $/l)

Abstract

The enhancement of the productivity of the solar desalination system, in a certain location, could be attained by a proper modification in the system design. Therefore, different design configurations could be found in literatures. However, the increase in the system productivity with high system cost may increase also the average annual cost of the distillate. Cost analysis of different design configurations of solar desalination units is essential to evaluate the benefit of modification from the economical point of view. The main objective of this work is to estimate the water production cost for different types of solar stills. In this paper 17 design configurations are considered. Systems with higher and lower values of productivity are considered in this investigation. A simplified model for cost analysis is applied in this study. The results show that, the best average and maximum daily productivity are obtained from solar stills of single-slope and pyramid-shaped. The higher average annual productivity for a solar still is about 1533 l/m^2 using pyramid-shaped while the lower average annual productivity is about of 250 l/m^2 using modified solar stills with sun tracking. The lowest cost of distilled water obtained from the pyramid-shaped solar still is estimated as 0.0756LE/l (about 0.0135 $/l) while highest cost from the modified solar stills with sun tracking is estimated as 1.288 LE/l (about 0.23 $/l).

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Introduction

Desalination technologies have been used for about a century in land-based plants and on ships to provide water for a crew. The regular use of desalination technologies accelerated after World War II, as the demand for fresh water in arid countries. The cost for desalination has been decreasing rapidly, especially in recent years with the introduction of efficient, more cost effective technologies. For solar distillation systems, sunlight has the advantage of zero fuel cost but it requires more space (for its collection) and generally more costly equipment. In principle, the water from a solar still should be quite pure. The slow desalination process allows only pure water to evaporate from the basin and collect on the cover, leaving all particulate contaminants behind. A solar still is a simple device which can be used to convert saline, brackish water into drinking water. Solar stills use exactly the same processes which in nature generate rainfall, namely evaporation and condensation. Its function is very simple; basically a transparent cover encloses a pan of saline water.

Desalination of brackish or sea water represents a consolidated system to resolve the water emergency. The main drawbacks to this solution however are high energy consumption and high cost. Therefore, it is imperative to evaluate the possibility of using local renewable resources to desalt water. Since high cost is the greatest hindrance to solar energy application. This paper presents water desalination technologies using solar energy. It is objected to estimate the water production cost for different types of solar distillation units. Review of some different configurations of solar distillation system will be followed by the economical analysis and comparison between these types.

Single basin solar still is a popular solar device used for converting available brackish or waste water into potable water. Because of its lower productivity, it is not widely used. Numerous modifications are investigated to improve the productivity of the still. Solar stills of desalination plant has low thermal efficiency and productivity. This could be improved by various passive and active methods. For examples, Fath et al. [1] presented an analytical study as well as thermal and economic comparisons between two solar still configurations: the pyramid and the single slope.

Samee et al. [2] presented the design and performance of a simple single basin solar still. A schematic diagram of the designed solar still is shown in Fig. 1. The average daily output of solar still based on data of 8 days in July 2004 was found to be 1.7 liters/day for basin area of 0.54 m^2. Efficiency of the still was calculated as 30.65% with a maximum hourly output of 0.339 liters/hr at 1300 hrs.

Kumar and Tiwari [3] presented the life cycle cost analysis of the single slope passive and hybrid photovoltaic (PV/T) active solar stills, based on the annual performance at 0.05 m water depth as shown in Fig. 2.

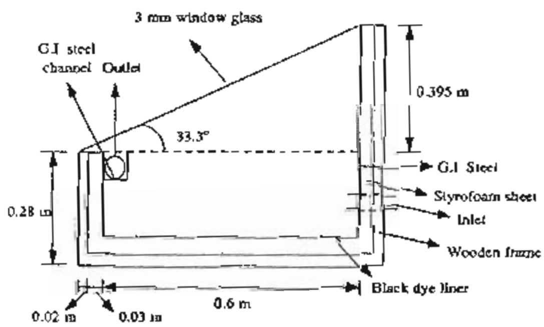

Fig. 1. Schematic diagram of the designed single basin solar still [2]

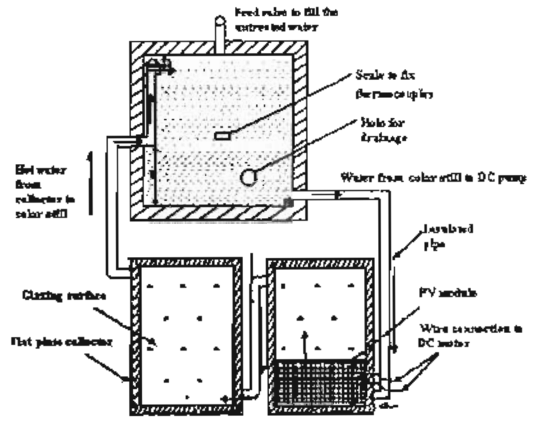

Fig. 2. Schematic top view of a hybrid (PV/T) active solar still [3].

The effect of coupling a flat plate solar collector on the productivity of solar stills (Fig. 3) was carried out by Badran and Tahaineh [4]. It was found that coupling of a solar collector with a still has increased the productivity by 36%.

The modified unit (Fig. 4) includes a solar parabolic trough (solar energy concentrator) with focal pipe and simple heat exchanger (serpentine) was studied by Abdel-Rehim and Lasheen [5]. Oil is flowing through the focal pipe and serpentine to heat water in the still. The results show that fresh water productivity is increased by an average of 18%, due to the modification.

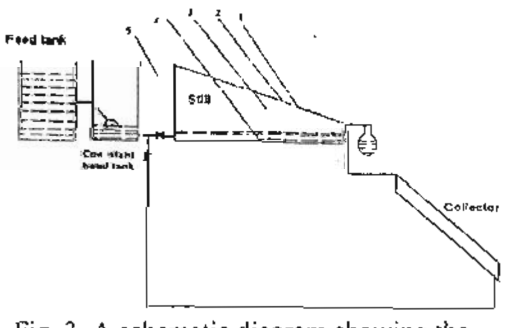

Fig. 3. A schematic diagram showing the arrangement of the still-collector systems [4].

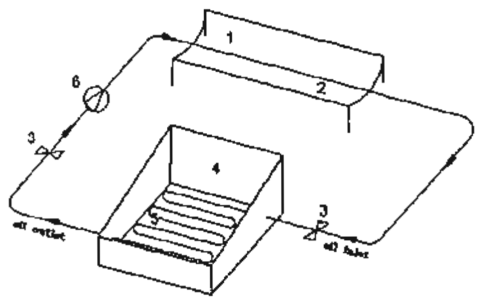

Fig. 4. Experimental set-up of the modified system. [5]. (1 parabolic trough, 2 oil pipeline, 3 valves, 4 solar still, 5 oil serpentine, 6 pump)

A sun tracking system was deployed for enhancing the single-slop solar still productivity by Abdallah and Badran [6]. A computerized sun tracking device was used for rotating the solar still with the movement of the sun. A comparison between fixed and sun tracked solar stills showed that the use of sun tracking increased the productivity for around 22%, due to the increase of overall efficiency by 2%. It can be concluded that the sun tracking is more effective than fixed system and it is capable of enhancing the productivity.

Al-Hinai et al. [7] performed a parametric study on a conventional pyramid double-sloped single-basin solar still (Fig. 5) under climatic conditions of Sultanate of Oman at the Gulf region. They reported that under optimum design conditions, the still tends to give an average annual solar yield of approximately 4 l/m^2 day.

Badran et al. [8] studied the performance of a solar still augmented with a flat-plate collector (Fig. 6). They concluded that the mass of distilled water production was increased by 231% in the case of tap water as a feed and by 52% in the case of salt water as a feed.

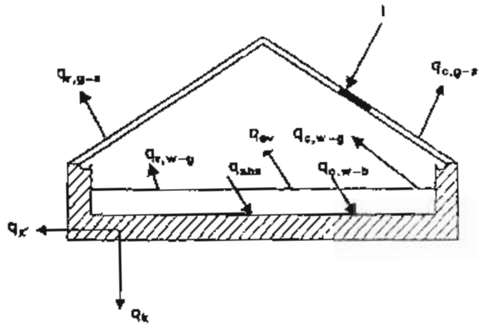

Fig. 5. Energy balance for the solar still [7]

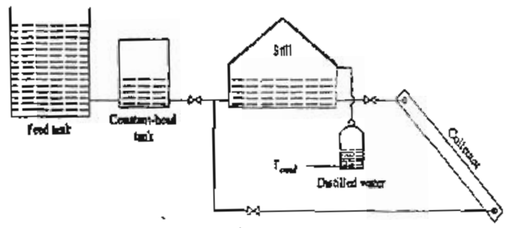

Fig. 6. A schematic diagram showing the arrangement of the still-collector systems [8]

The productivity of the single basin solar still was augmented by integrating fins at the basin plate by Velmurugan et al. [9]. To enhance the productivity of solar still, it was modified with fin, black rubber, sand, pebble and sponges (Fig. 7). It was found that the evaporation rate increased by about 53% when fins were integrated at the basin plate.

Velmurugan et al. [10] compared the performance of ordinary single basin solar still and wick type still (Fig. 8). To enhance evaporation of the still basin water, fins and sponges were integrated at the basin of the still. It was found that 29.6% productivity increased, when wick type solar still was used, 15.3% productivity increased when sponges were used and 45.5% increased when fins were used.

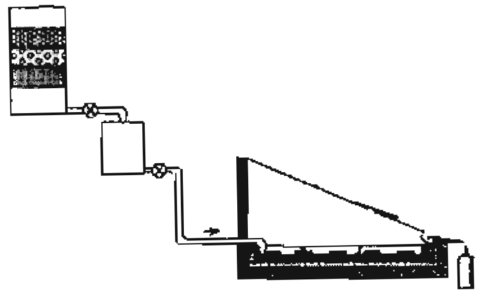

Fig. 7. Storage tank and a single basin solar still [9]

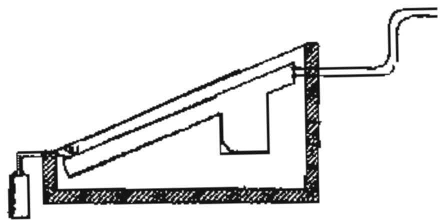

Fig. 8. Cross-sectional view of the ordinary solar still [10]

A simple transportable hemispherical solar still (Fig. 9) was designed and fabricated by Ismail [11] and its performance was experimentally evaluated under outdoors of Dhahran climatic conditions. It was found that over the hours of experimental testing through daytime, the daily distilled water output from the still ranged from 2.8 to 5.7 l/m^2 day.

Velmurugan et al. [12] studied a stepped still with two different depth of trays. The basin plate contains twenty five trays with 10 mm depth and twenty five trays with 5 mm depth. Theoretical and experimental analyses were made for fin type, sponge type, and combination of fin and sponge type stepped solar still. It was found that when the fin and sponge type stepped was used, the average daily water production has been found to be 80% higher than ordinary single basin solar still.

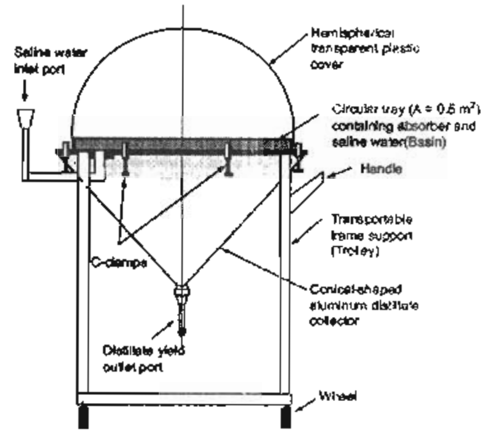

Fig. 9. Schematic diagram of the new transportable hemispherical solar still [11]

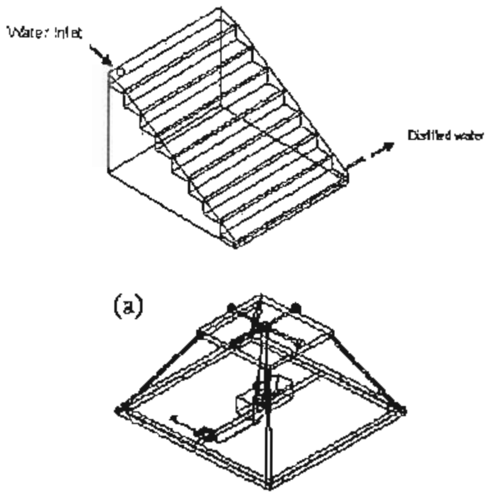

Fig. 10. Isometric view of the step-wise water basin and three-dimensional view of the sun tracking distiller, base, motor and bearing [13]

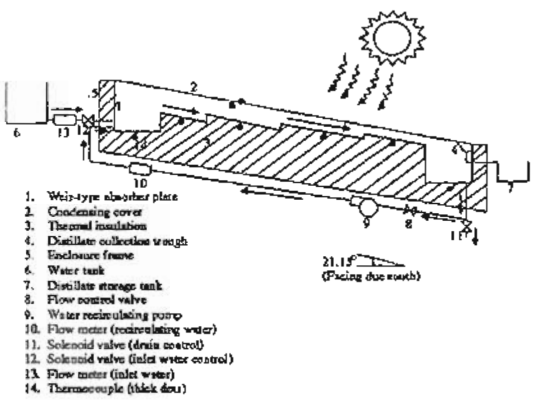

Fig. 11. Weir-type inclined solar still [14]

Sun tracking systems were used by some researchers to enhance the desalination production. Abdallah et al. [13] studied the performance of a traditional single slope solar still through three design modifications: addition of internal reflecting mirrors on all interior sides of still, using step-wise water basin instead of flat basin, and coupling the solar still with a sun tracking system (Fig. 10). The inclusion of internal mirrors improved the system thermal performance up to 30%, while step-wise basin enhanced the performance up to 180% and finally the coupling of the step-wise basin with sun tracking system gave the highest thermal performance with an average of 380%.

Sadineni et al [14] studied weir-type inclined solar (Fig. 11). A weir-type solar still was proposed to recover rejected water from the water purifying systems for solar hydrogen production. The results show that the productivity of the weir-type still is approximately 20% higher.

A solar pond (SP) is a thermal solar collector that includes its own storage system. A solar pond collects solar energy by absorbing direct and diffuse sunlight. Therefore, Velmurugan and Srithar [15] presented a comparison between theoretical and experimental analysis of a mini solar pond assisted solar still. In a mini solar pond, experiments were conducted for different salinity (Fig. 12). Effect of sponge cubes in the still, effect of integrating mini solar pond with the still and combination of both were discussed. It was found that the average daily production of solar still was found to be increased considerably, when it is integrated with a mini solar pond.

In an attempt to improve the daily productivity of the single effect solar stills, a single-slope single-basin solar still integrated with a shallow solar pond (SSP) (Fig. 13) was studied by El-Sebaii et all [16] to perform solar desalination at a relatively high temperature. The resulted show that the annual average values of the daily productivity and efficiency of the still with the SSP were found to be higher than those obtained without the SSP by 52.36% and 43.80%, respectively.

The effect of adding a passive condenser on the performance of the single slope, basin type solar still was studied by few authors. Analysis of a parallel single and double glass solar still with separate condenser (Fig. 14) was studied by El-Bahi and Inan [17] with minimum inclination (4°) investigated experimentally. The results show that the solar still operated without a condenser yields decrease about 70% of compared with a condenser use.

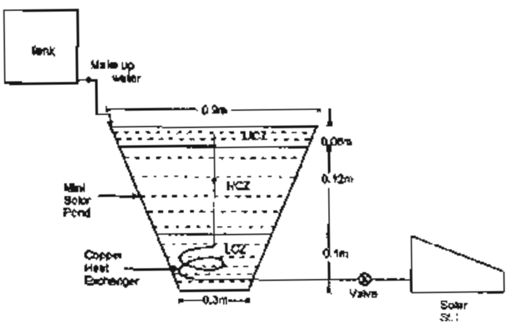

Fig. 12. A mini solar pond and a solar still [15]

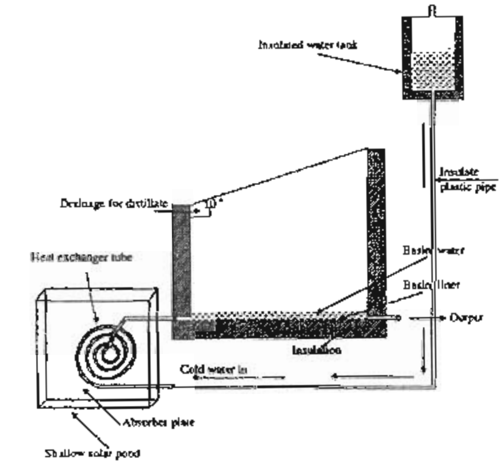

Fig. 13. A schematic diagram of a single-basin solar still coupled with the shallow solar pond [16].

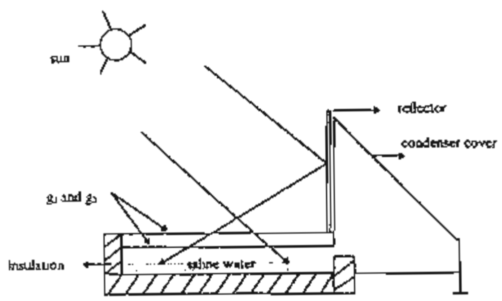

Fig. 14. Solar still with inbuilt condenser. [17]

Economic analysis

Many factors affect the cost of distillate obtained from a solar desalination unit. Both capital and running (and so the total) costs are influenced by unit size, site location, feed water properties, product water required quality, qualified staff availability, etc. The main economic advantages of solar desalination should not require much infrastructure, and its simple to locally design, install, operate and maintain.

The better economic return on the investment depends on the production cost of the distilled water and its applicability. Economical analysis of water desalination unit is given by Fath et al. [1], Kumar and Tiwari [3] and Govind and Tiwari [18]. The capital recovery factor (CRF), the fixed annual cost (FAC), the sinking fund factor (SFF), the annual salvage value (ASV), average annual productivity (M) and annual cost (AC) are the main calculation parameters used in the cost analysis of the desalination unit. The annual maintenance operational cost (AMC) of the solar still is required for regular filling of brackish water, collecting the distilled water, cleaning of the glass cover, removal of salt deposited (scaling) and maintenance of the DC pump. Higher the depth of water, less frequent will be the filling of water in the basin. As the system life passes on, the maintenance on it also increases. Therefore, 10% of net present cost has been considered as maintenance cost. Finally, the cost of distilled water per liter (CPL) can be calculated by dividing the net annualized cost of the system (AC) by annual yield of solar still (M). The above mentioned calculation parameters can be expressed as [1]:

$$CRF=i(1+i)^n/[(1+i)^n-1] \quad (1)$$

$$FAC = P\ (CRF) \quad (2)$$

$$SFF = i/[(1+i)^n-1] \quad (3)$$

$$S= 0.2\ P \quad (4)$$

$$ASV = (SFF)\ S \quad (5)$$

$$AMC=0.15\ FAC \quad (6)$$

$$AC = FAC + AMC - ASV \quad (7)$$

$$CPL = AC/M \quad (8)$$

Where:

P is the present capital cost of desalination system

i is the interest per year, which is assumed as 12%

n is the number of life years, which is assumed 10 years in this analysis.

In this study, the prices of raw materials, according to the Egyptian market.

Table 1. The different review types of solar stills

No. Ref.	Type of solar still
Fath et al.[1]	Single-slope
Samee et al. [2]	Single-slope
Kumar and Tiwari [3]	Single-slope
Kumar and Tiwari [3]	With solar collector
Badran and Tahaineh [4]	With solar collector
Abdel-Rehim and Lasheen [5]	With solar concentrator
Abdallah and Badran [6]	With sun tracking
Fath et al.[[1]	Pyramid-shaped
Al-Hinai et al. [7]	Pyramid-shaped
Badran et al.[8]	Pyramid with collector
Velmurugan et al. [9]	With fin type
Velmurugan et al. [10]	With wick and fin type
Ismail [11]	transportable hemispherical
Velmurugan et al. [12]	Stepped with fins and sponges
Abdallah et al. [13]	Stepped with sun tracking
Sadineni et al. [14]	A weir-type
Velmurugan and Srithar [15]	With sponge and pond
El-Sebaii et al. [16]	With a shallow solar pond
El-Bahi and Inan [17]	With separate condenser

Results and discussions

The solar radiation of the different solar stills is shown in Fig. 15. The figure indicates the maximum solar radiation occurs in pyramid-shaped [7] where the solar radiation is about 1200 W/m^2. The average and minimum solar radiation is about 800 and 700 W/m^2.

The average and maximum daily productivity of the different solar stills is shown in Figs. 16 and 17. The figures indicate that the best solar stills of single-slope and pyramid-shaped [1], pyramid-shaped [7], single-slope with solar collector [3], single-slope with sponge and pond [15] and single-slope with separate condenser [17]. The maximum solar still productivity occurs in single-slope and pyramid-shaped [1] and [7] where the solar radiation is about 850 and 1200 W/m^2 respectively. The average and maximum daily solar still yield per day is about 5.9 and 8.5 l/m^2. This average yield will be used next to conduct a simple cost analysis of the solar still under Egypt climate.

Fig. 18 shows the average annual productivity for different types of solar stills. The results obtained show that higher average annual productivity for a solar still is having a capacity of 1533 and 1511 l/m^2 using pyramid-shaped [1] and [7]. The lower average annual productivity is about of 250 l/m^2 using modified solar stills with sun tracking [6].

Fig. 19 shows the average costs of distilled water for different types of solar stills. The results obtained show that best water production cost for a solar still having a capacity of 1511 and 1533 l/m^2 is around 0.0756 and 0.1736 LE/l (about 0.0135 and 0.031 $/l) using pyramid-shaped [1] and [7]. The modified solar stills with sun tracking [6], transportable hemispherical [11] and solar collector [3] give the maximum water production cost are around 1.288 and 1.008 LE/l (about 0.23 and 0.18 $/l).

Conclusion

From the above review and economical analysis of the different methods and modifications used to improve the productivity of solar stills, the following conclusions could be drawn

1-The best average and maximum daily productivity are obtained from solar stills of single-slope and pyramid-shaped

2-The higher average annual productivity for a solar still is having a capacity of 1533 and 1511 l/m^2 using pyramid-shaped while the lower average annual productivity is about of 250 l/m^2 using modified solar stills with sun tracking.

3-The lowest cost per l of distilled water obtained from the pyramid-shaped solar still and is estimated as 0.0756 and 0.1736LE/l (about 0.0135 and 0.031 $/l while highest cost from the modified solar stills with sun tracking is estimated as 1.288 LE/l (about 0.23 $/l).

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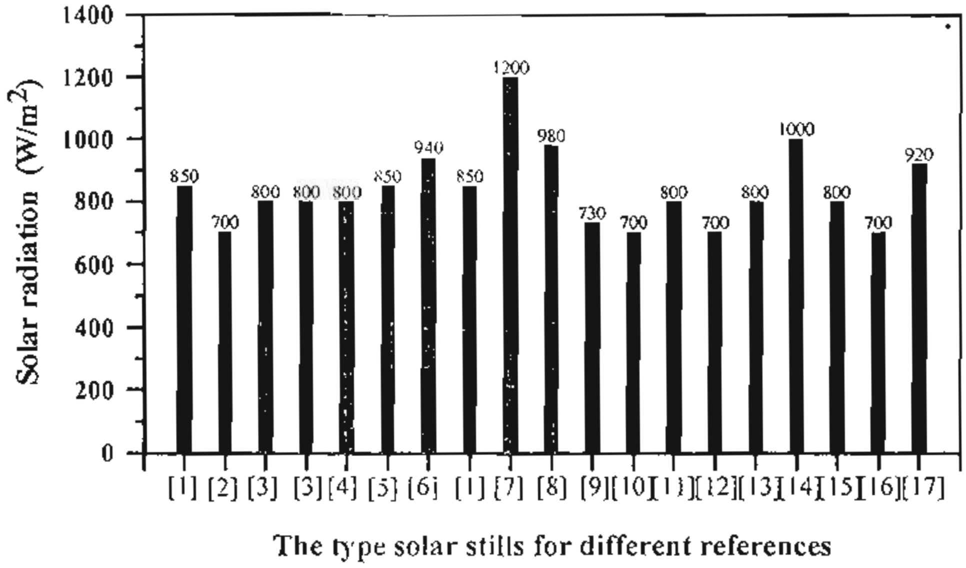

Fig. 15. The solar radiation for different types of solar stills

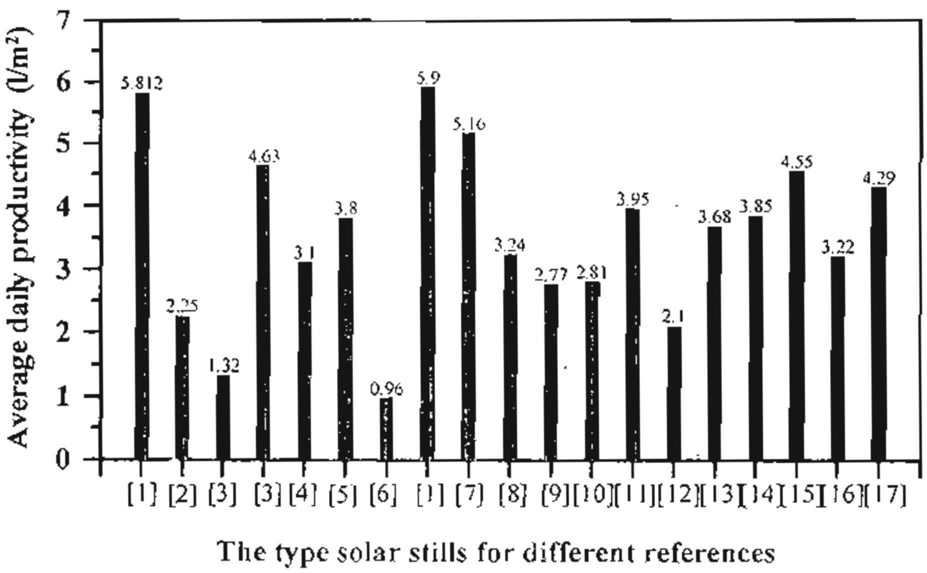

Fig. 16. The average daily productivity for different types of solar stills

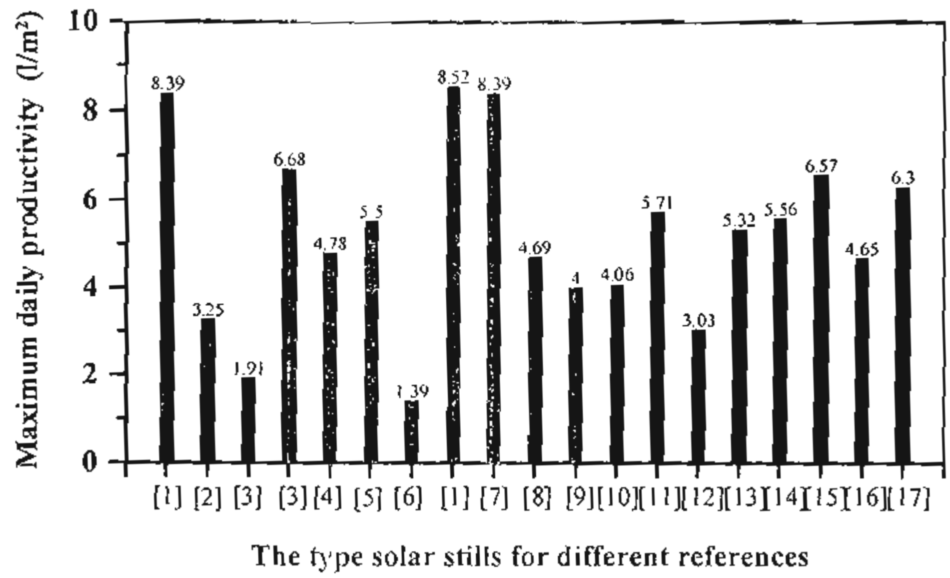

Fig. 17. The maximum daily productivity for different types of solar stills

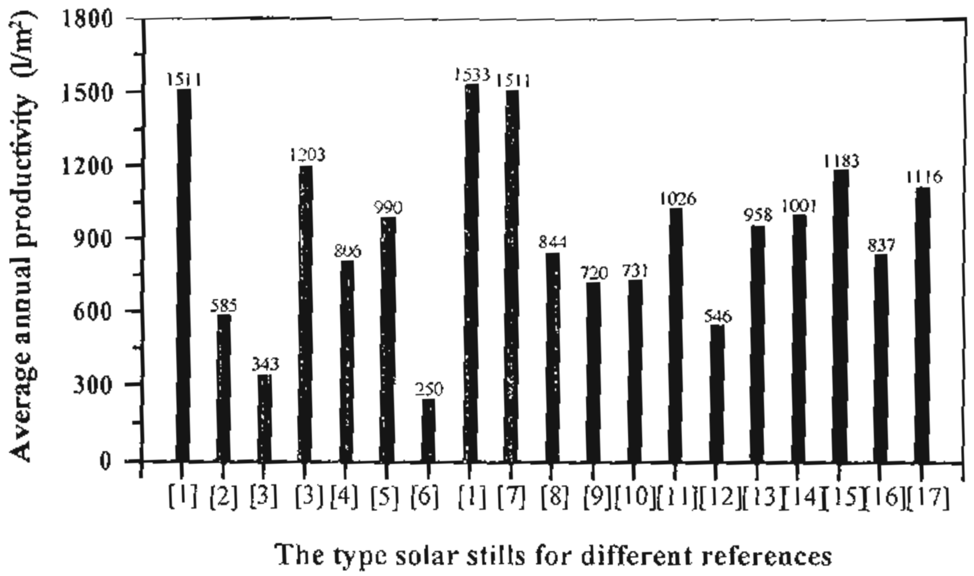

Fig. 18. The average annual productivity for different types of solar stills

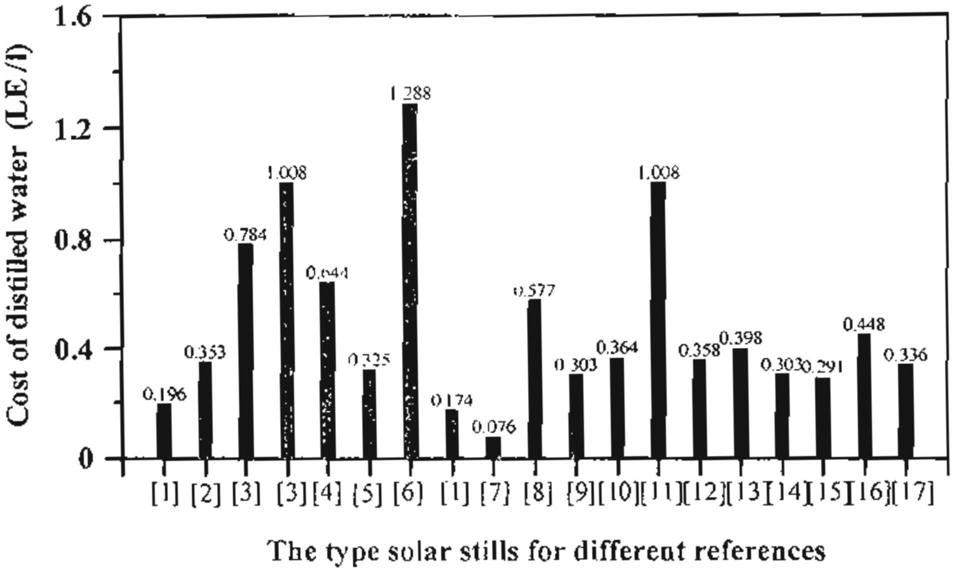

Fig. 19. The average costs of distilled water for different types of solar stills