Investigation of Multi-Effect Humidification (MEH) - Dehumidification Solar Desalination System Coupled With Solar Central Receiver

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Abstract

In this paper, with the bounty of ALLAH and his conciliation, a new multi-effect humidification (MEH)-dehumidification solar desalination system coupled with solar central receiver has been designed, installed and out door tested in the faculty of Engineering, Suez Canal University, Port Said, Egypt. The heat collection part of the system (central receiver with 28 heliostats around it in three circles) has been designed to provide the hot water to the desalination chamber. The desalination chamber is divided into humidifier and dehumidifier towers. The circulation of air in the two towers is being maintained by natural convection. It was found that the productivity of the system increases when the sprayer position is at the middle of the evaporator tower. The experimental test results showed that, increase of seawater mass flow rate from 0.07 liter/s to 0.09 liter/s increases the productivity of the system by 10%. Two modifications were introduced on the desalination chamber to enhance the desalination system productivity. The first modification was using water jacket at one side of the dehumidifier tower to increase the condensation surface. The second modification was to use seven flat mirrors to concentrate solar radiation on one side of the humidifier tower to heat the humid air. The test results showed that, the first modification increases the system productivity by 15% and the use of the second modification increases the system productivity by 12%. It was found also that the use of the two modifications together increases the system productivity by 22%. The productivity of the system in this case was 3.5 kg/day.
Keywords: Solar energy - Solar Desalination – Multi-effect humidification (MEH)- dehumidification – Central receiver .

Introduction

Water, like energy in the late 1970s, will probably become the most critical natural resource issue facing most parts of the world by the start of the next century [1]. In many arid regions of the world, and especially in the Middle East, where conventional sources of fresh water (e. g., rivers, lakes and groundwater) are not readily available, seawater desalination will continue to supply drinking water. Desalination is a water treatment process that converts brakish or saline water to fresh water by removing dissolved minerals from the water. A proven technology that has been used for many years, desalination is increasingly common in areas with scarce water supplies. However, because of its relatively high cost, it is generally used only if fresh water supplies are limited [2]. Water desalination technologies can be categorized on the basis of the energy used to run them, usually thermal or electric. The technologies utilizing thermal energy are known as the multi-stage flash (MSF), multiple-effect distillation (MED) and vapor compression (VC). The desalination technologies that use electric energy rely on a membrane system, such as reverse osmosis (RO) and electro dialysis (ED). There are also other technologies that rely on solar energy or combined electric and thermal energy. Each of these technologies has advantages and disadvantages, based on the quantity and quality of the required water and the location. Desalination processes require large amounts of thermal or electric energy; however, advances in desalination technology continue to make these processes more efficient [3]. Recent investigations have focused on the use of renewable energy to provide the required power for the desalination processes. The most popular renewable energy source being solar energy [4]. An emerging technology for smaller scale desalination systems is solar multi-effect humidification (MEH)-dehumidification. This process uses solar energy to evaporate fresh water, which is condensed on a cool surface and collected. Solar desalination systems are simply and easy to operate and maintained. They are also environmentally friendly because they do not require fossil fuels. In locations with abundant sunshine, such as Egypt, solar desalination is a potentially viable option, especially for small-scale plants in remote locations. Multi-effect humedification-dehumidification solar system was suggested as an efficient method for the production of desalinated water , initially for small quantity in remote arid areas [5&6]. In this paper a new multi-effect humidification-dehumidification (MEH) solar desalination system (a desalination chamber coupled with a solar central receiver) has been designed, installed and outdoor tested in the faculty of Engineering, Suez Canal University, Port Said, Egypt. The tests have been carried out for Port Said climatic conditions (31°17' N latitude, 32°12' E longitude). The system uses a central receiver with twenty-eight heliostats arranged around it in three circles as a heat source. The desalination chamber consists of humidifier (evaporator) and dehumidifier (condenser) towers. The circulation of air in the two towers was obtained by natural convection. In this work an experimental investigation on the proposed solar distillation system had been carried out. The study includes design, construction and testing of the system (Figs.1&2).

The Principle of Solar Central Receiver

Central receivers are one of the most promising applications in the utilization of solar energy to produce heat. Basically, reflecting surfaces called heliostats are laid around a central tower and used to reflect solar irradiance to a receiver on the top of the tower. Radiation absorbed by the receiver has then utilized to produce heat. The heliostat field consists of a number of flat or focusing mirrors (heliostats) distributed in a surround-field arrangement (360° arrangement). Each heliostat is continuously rotating around two axes to follow the sun so that solar ray is always reflected to the central receiver. This means that the tilt and the orientation angles of each heliostat are continuously adjusted. The reflected radiation from the heliostat field is absorbed by the receiver surface. Heat is then removed from the receiver by means of heat removal fluid. The overall dimensions and costs of a central receiver system depend on the design of the system. The designer of a central receiver system faces several problems and challenges to economically optimize his design. Among these challenges are: the selection of the heliostat type and its dimensions; the spacing between the heliostats in the field; the field dimensions; the tower height; the receiver geometry and type; the method of heat removal from the receiver, etc. The heliostat has either a flat (non-focusing) or a focusing surface. In most cases glass mirrors are used as the reflecting surface.

The mathematical equations required to determine the tilted angle and the orientation angle of a given heliostat in a field were given by many workers [7]. The center of a heliostat is defined in terms of the radius r and the azimuth angle ψ_p , where r is the horizontal radial distance from the center of the tower, and ψ_p is the azimuth angle of the heliostat arrangement measured from the south direction as depicted in Fig.3. The center of the receiver is located at a height H above point O. Figure 4 depicts the heliostat tilt angle γ. The heliostat tilt angle is the angle between the unit vector N normal to the heliostat surface and the vertical direction. The heliostat azimuth angle (also called heliostat orientation angle) is the angle between the horizontal projection of the unit vector N and the south direction, with clockwise rotation as positive. The heliostat tilt angle "s" according to [7] is given by:

$$\cos\ s = \frac{\cos\theta_z + \cos\theta_r}{\left\{2 + 2[\cos\theta_z \cos\theta_r - \sin\theta_z \cos(\psi - \psi_p)\sin\theta_r]\right\}^{1/2}} \tag{1}$$

Where θ_z and ψ are the solar zenith and azimuth angles, respectively and θ_r is the receiver altitude angle which is defined as follows:

$$\theta_r = \tan^{-1} r / H \tag{2}$$

The heliostat azimuth angle γ (orientation angle) is given by:

$$\cos\ (\gamma - \psi_p) = \frac{\sin\theta_z \cos(\psi - \psi_p) - \sin\theta_r}{\left\{[\sin\theta_z \cos(\psi - \psi_p) - \sin\theta_r]^2 + [\sin\theta_z \cos(\psi - \psi_p)]^2\right\}^{1/2}} \tag{3}$$

The heliostat angles s and γ given by the above equations are functions of the

$$\sin\ (\gamma - \psi_p) = \frac{\sin\theta_z \sin(\psi - \psi_p)}{\left\{[\sin\theta_z \cos(\psi - \psi_p) - \sin\theta_r]^2 + [\sin\theta_z \cos(\psi - \psi_p)]^2\right\}^{1/2}} \tag{4}$$

sun position and the heliostat position, i.e., they are functions of θ_z, $\psi - \psi_p$ and r / H.

The heliostat layout configuration around the tower could be detrimental factor in the amount of energy collected by the receiver. Improper heliostat layout results in excessive losses in the energy reflected by the heliostat surface, in addition to the increase of the heliostat cost. Two configurations were used: a rectilinear layout configuration and a radial layout configuration. Radial staggered layout configuration is proved to be the best layout arrangement by many investigators in recent installations[8]. The simplest criteria to primary layout the heliostat in the field is to minimize or to eliminate the losses due to the so-called shadowing and blocking. Shadowing means that the reflecting surface (or part of it) of one heliostat comes in the shade area of another heliostat, whereas blocking means that the reflected rays (or part of them) by one heliostat is blocked by the back surface of another heliostat.

Several research studies were carried out to recommend the radial and azimuth spacing between heliostats in a radial staggered field. A common feature between these works is to minimize or eliminate the losses due to shadowing and blocking. In many cases additional criteria were considered. Several researchers recommended the following constant azimuth spacing[9]:

$$S_\psi / D = 2.1 \quad (5)$$

On the contrary, several correlations were recommended in the literature for the radial spacing S_r[10],

$$S_r / D = 0.2 + r / H \quad (6)$$

The Principle of Desalination Chamber

The main idea of the multi-effect humidification (MEH)-dehumidification solar desalination system based on the evaporation of water and the condensation of steam to and from humid air. The humid air circulation driven by natural convection between evaporator tower (humidifier) and condenser tower (dehumidifier) as shown in Figs.5&6. Evaporator and condenser are located in the same insulated box. The heated seawater from central receiver is distributed onto the evaporator tower through a vertically hanging sprayer and is slowly trickling downwards. The condenser unit is located opposite to the evaporator. Here the saturated air condenses on a single tube copper coil as shown in Fig.6. Water with ambient temperature was used as a coolant for the condenser. The distillate runs down to a collecting tank. Two modifications were introduced on the desalination chamber to enhance the desalination system productivity. The first modification was using water jacket at one side of the dehumidifier tower to increase the condensation surface. The second modification was to use seven flat mirrors to concentrate solar radiation on one side of the humidifier tower (0.003 m ordinary window glass) to heat the humid air to increase the system productivity

Test Rig Description

A schematic diagram of the proposed multi-effect humidification (MEH)-dehumidification solar desalination system is shown in Figs 1&2. It consists of a desalination chamber (0.5m x 0.5m x 0.5m) made of galvanized iron sheet (0.003 m thick) formed by bending and assembled by soldering. It is divided into two parts, evaporator tower (humidifier) and condenser tower (dehumidifier) as shown in Figs.5&6. The heated seawater from central receiver is distributed onto the evaporator tower through a vertically hanging sprayer and is slowly trickling downwards. The condenser unit is located opposite to the evaporator. The condenser consists of a 0.025 m single tube copper coil. The insulated desalination chamber is coupled with a solar central receiver by means of a pump to transport the heat from the solar central receiver to the brine in a 0.025 m single tube copper coil. A PVC pipe is used for the supply of seawater. The whole chamber is almost vapor-tight; silicon rubber is used as a sealant because it remains elastic for quite long time. The central receiver system consists of a 3.0 m tall steel structure tower with a 0.5m x 0.5m receiver on the tower top as shown in Fig.2. The central receiver used in seawater heating is an insulated waterproof box containing dark four sides absorber plates under a transparent cover (0.003 m thick ordinary window glass). The box is made of galvanized iron sheet (0.003 m thick) formed by bending and assembled by soldering. The dark absorber (galvanized iron sheet 0.003 m thick.) catch up heat from sunlight that passes through the cover, and then gives the heat up to the sea water flowing in a copper single tube coil past the absorber surface (see Fig.7). A 28 (05m x 0.5m) two axis tracking mirrors (heliostats) that redirect and focus solar radiation on the central receiver are used. The 28 heliostats are arranged around the steel tower in three circles. The first circle consists of 4 heliostats and has a 6m diameter. The second circle consists of 8 heliostats and has a 9 m diameter. The third circle consists of 16 heliostats and has a 12 m diameter. Two modifications were introduced on the desalination chamber to enhance the desalination system productivity. The first modification was using water jacket at one side of the dehumidifier tower to increase the condensation surface. The second modification was to use seven flat mirrors (0.5m x 0.5 m) to concentrate solar radiation on one side of the humidifier tower (0.003 m ordinary window glass) to heat the humid air to increase the system productivity. Experiments have been carried out outdoors during summer of 2003. The global solar radiations on a horizontal surface and on the central receiver are measured using a silicon cell pyranometer model (3120). Calibrated NiCr-Ni thermocouples are used to measure the temperatures at different points in the desalination chamber. The ambient temperature has been also measured.

Results and Discussion

Experimental tests were carried out in several days during June 2003 to ensure the same climatic conditions for all tests. The results obtained are summarized in the following figures. Fig.8 shows the accumulative productivity of the system when the sprayer distance from the top of the chamber (x) equal to 0.15 m and the seawater mass flow rate is 0.07 liter/s. Fig.9 shows the accumulative productivity of the system when the sprayer distance from the top of the chamber (x) equal to 0.25 m (i.e in the middle of the evaporator tower) and the seawater mass flow rate is 0.07 liter/s. It can be seen from the above two curves that the productivity of the system increases when the sprayer position is at the middle of the evaporator tower. And this is due to the fact that this position of the sprayer gives better distribution for the humid air in the chamber. Fig.10 shows the accumulative productivity of the system when the sprayer distance from the top of the chamber (x) equal to 0.15 m and the seawater mass flow rate is 0.09 liter/s. Fig.11 shows the accumulative productivity of the system when the sprayer distance from the top of the chamber (x) equal to 0.15 m and the seawater mass flow rate is 0.09 liter/s. From the above four curves it can be noticed that the increase of the seawater mass flow rate increases the productivity of the desalination chamber. The hourly temperature variation of the seawater and ambient is presented in Fig.12. Figs. 13&14 show a typical measurement of solar radiation intensity on a horizontal surface and on the central receiver. It can be seen from the above two curves that the use of heliostats around the central receiver increases the solar radiation intensity. Fig.15 shows the productivity of the desalination system with the first modification. It can be seen from the above curve that the first modification (using water jacket at one side of the dehumidifier tower to increase the condensation surface) increases the system productivity by 15%. Fig.16 shows the productivity of the desalination system with the second modification. It can be seen from the above curve that the use of the second modification (using seven flat mirrors to concentrate solar radiation on one side of the humidifier tower (0.003 m ordinary window glass) to heat the humid air to increase the system productivity) increases the system productivity by 12%. The effect of using the two modifications together is presented in Fig.17. It can be seen from the curve that the use of the two modifications together increases the system productivity by 22%. The productivity of the system in this case was 3.5 kg/day.

Conclusion

A new multi-effect humidification (MEH) dehumidification system has been designed, installed and out door tested in the faculty of Engineering, Suez Canal University, Port Said, Egypt. The system cosists of an insulated desalination chamber coupled with a solar central receiver. The desalination chamber divided into evaporator tower and condenser tower. A 28 heliostats are arranged around the central receiver in three circles. Two modifications were introduced on the desalination chamber to enhance the desalination system productivity. The first modification was using water jacket at one side of the dehumidifier tower to increase the condensation surface. The second modification was to use seven flat mirrors to concentrate solar radiation on one side of the humidifier tower (0.003 m ordinary window glass) to heat the humid air to increase the system productivity. The system was found to be suitable to provide drinking water for population or remote arid areas. It can be seen from the above test results that:

1- The productivity of the system increases when the sprayer position is at the middle of the evaporator tower (x= 0.25 m). And this is due to the fact that

2- this position of the sprayer gives better distribution for the humid air in the chamber.
3- The increase of seawater mass flow rate from 0.07 liter/s to 0.09 liter/s increases the productivity of the system by 10%.
4- The first modification increases the system productivity by 15%.
5- The second modification increases the system productivity by 12%.
6- The use of the two modifications together increases the system productivity by 22%. The productivity of the system in this case was 3.5 kg/day.

Nomenclature

D length of the side of a square heliostat
H height of tower
r radial distance of center of heliostat measured from base of tower
s heliostat tilt angle with the ground plane
S_r spacing of heliostats along the radial distance of the heliostat field
S_ψ spacing of heliostat s along the azimuthal direction of the heliostat field
x sprayer distance from the top of the chamber
θ_r receiver altitude angle measured from center of heliostat
θ_z solar zenith angle
ψ solar azimuth angle , measured from south in clockwise direction
ψ_p heliostat arrangement angle, measured from south in clockwise direction

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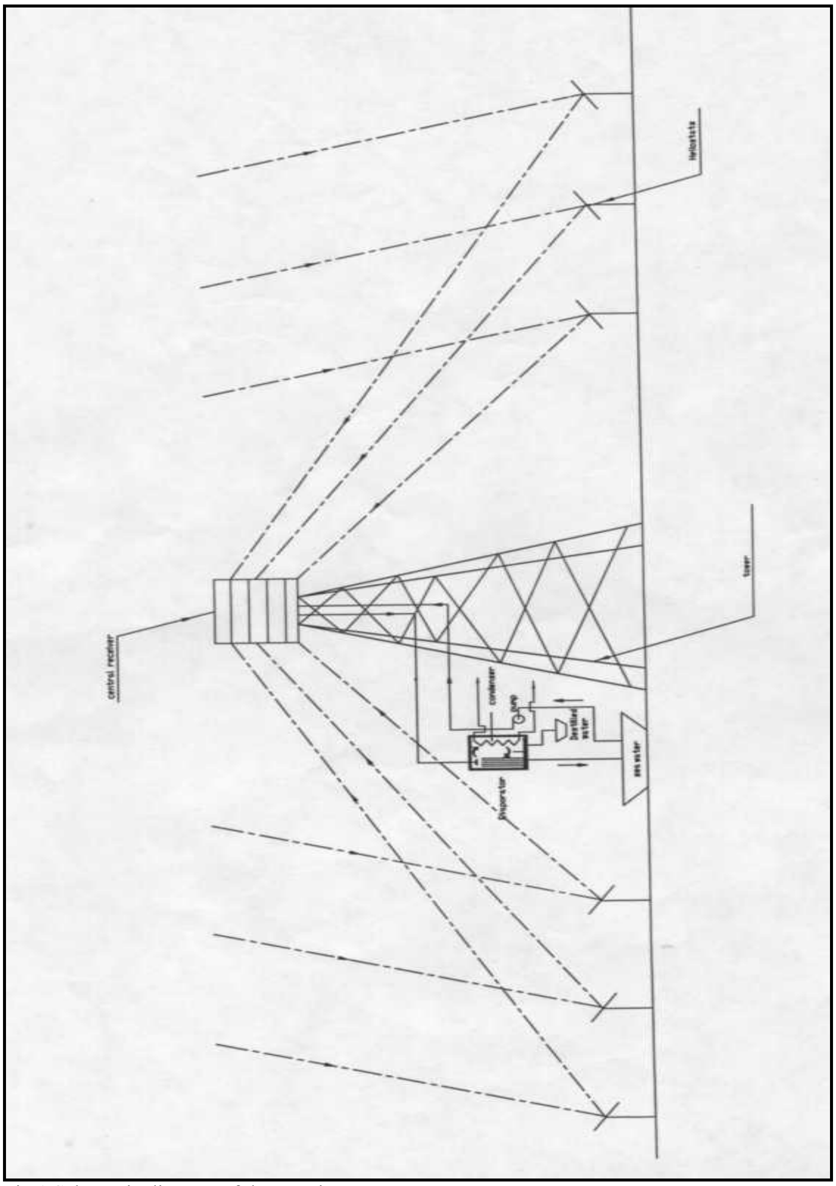

Fig.1 Schematic diagram of the test rig

Fig.2 Photo of the test rig

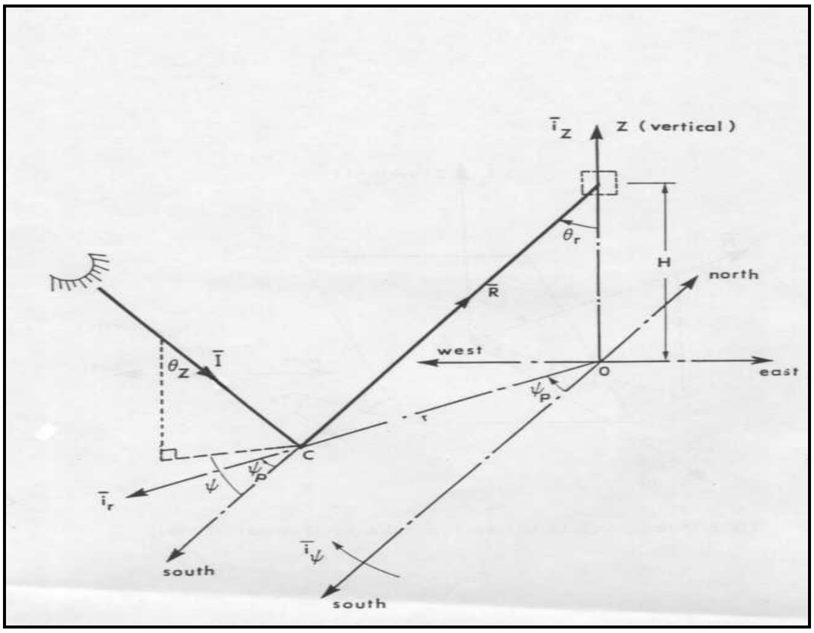

Fig.3 Geometry of position of heliostat with respect to tower and the reflection of a solar ray [7]

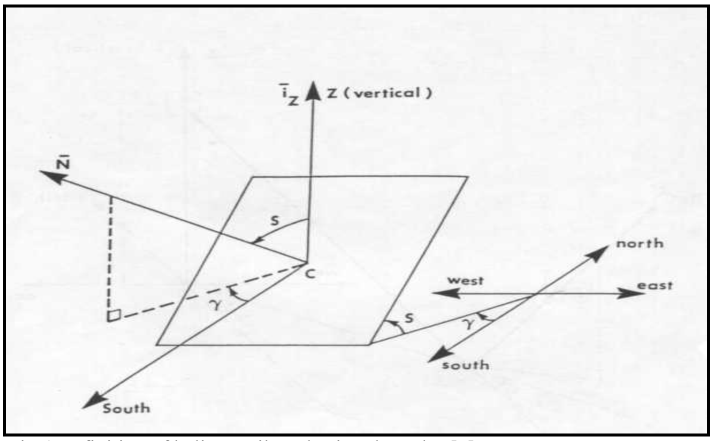

Fig.4 Definition of heliostat tilt and azimuth angles [7]

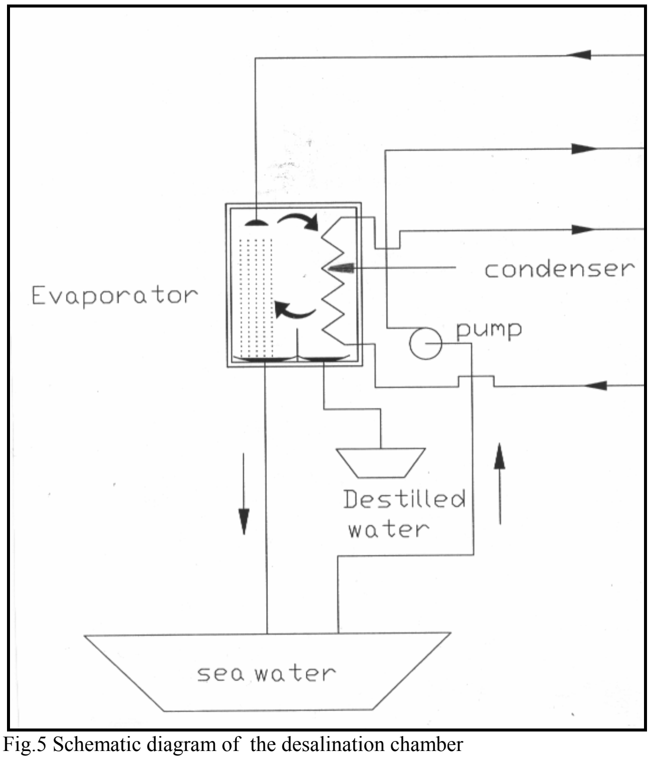

Fig.5 Schematic diagram of the desalination chamber


Fig.6 Photo of the desalination chamber


Fig.7 Central receiver with single tube copper coil on the absorber surface

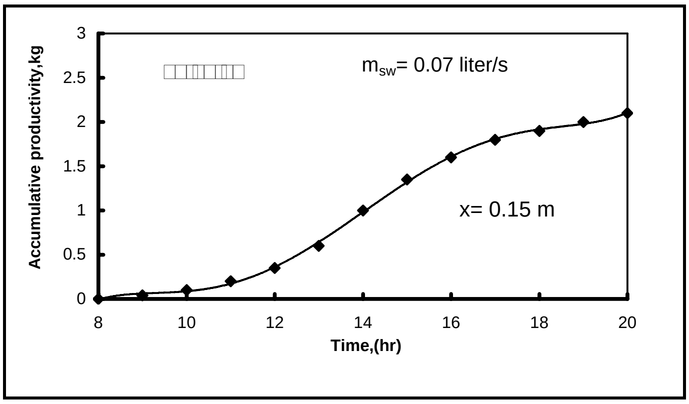

Fig.8 The hourly accumulative productivity (x=0.15 m, m_{sw}= 0.07 liter/s)

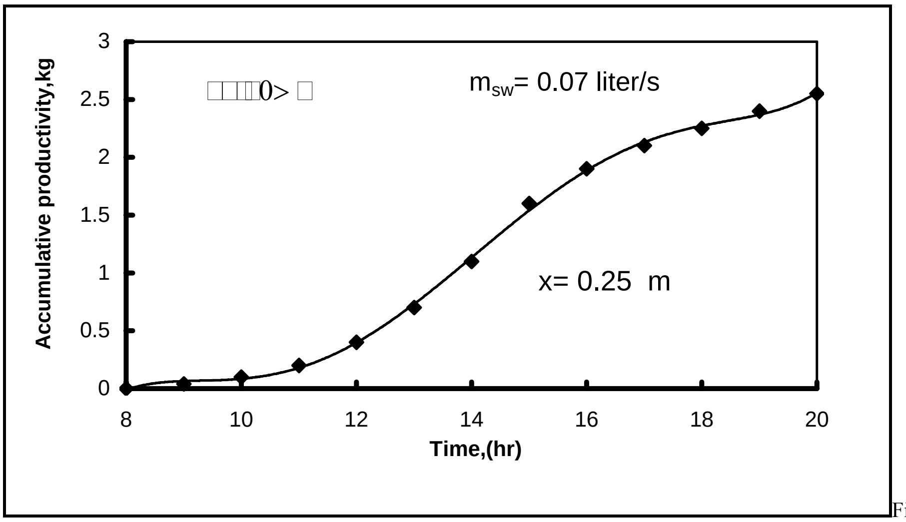

Fig. 9 The hourly accumulative productivity (x=0.15 m, m_{sw}= 0.07 liter/s)

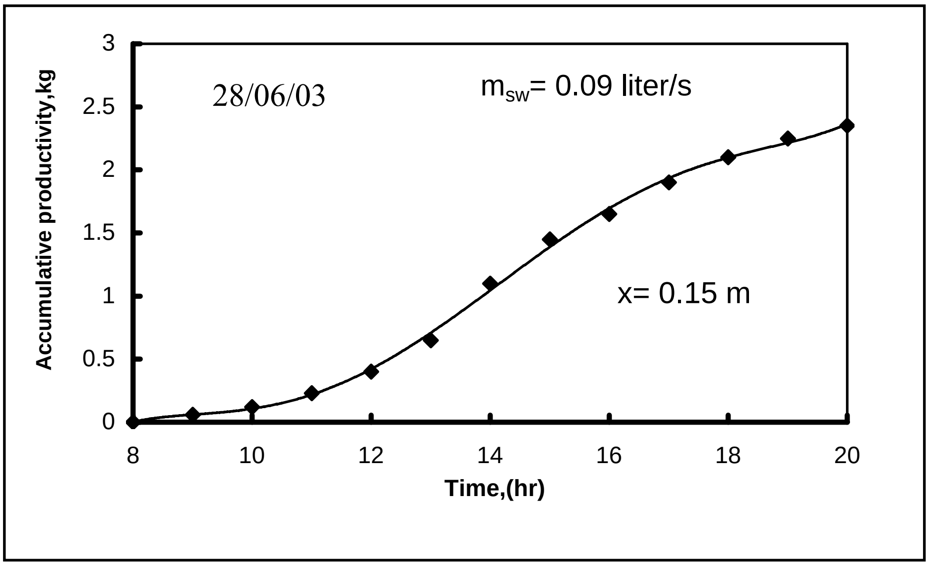

Fig. 10 The hourly accumulative productivity (x=0.15 m, m_{sw}= 0.09 liter/s)

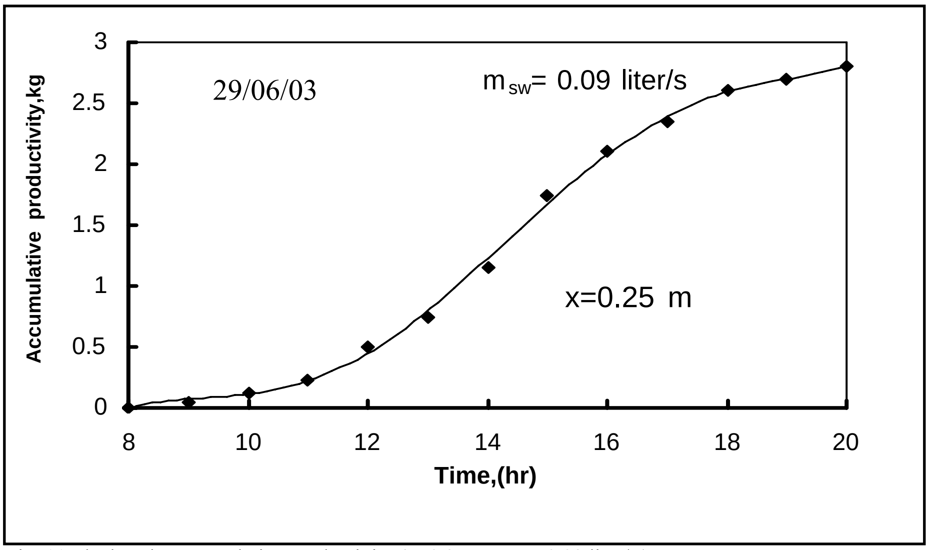

Fig. 11 The hourly accumulative productivity (x=0.25 m, m_{sw}= 0.09 liter/s)

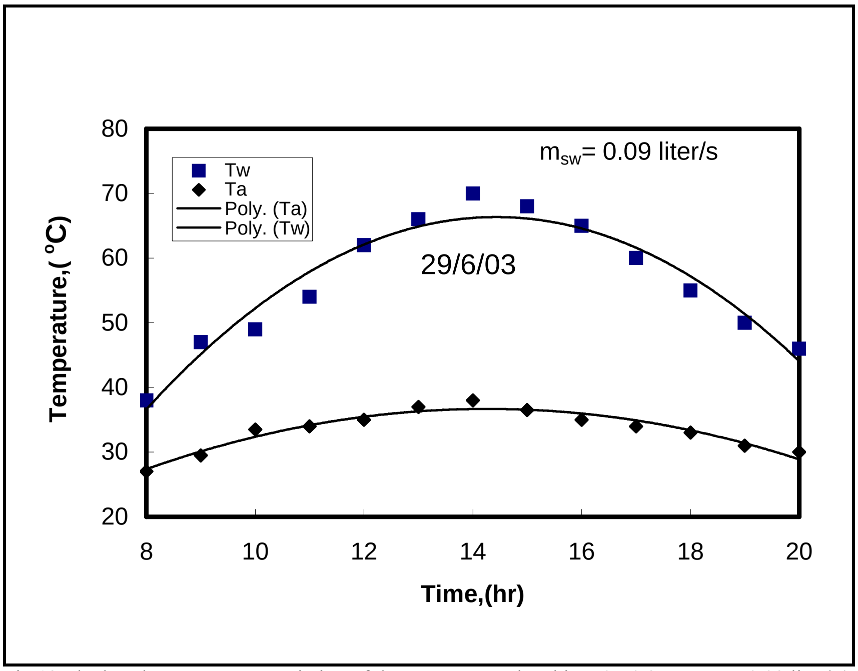

Fig.12 The hourly temperature variation of the sea water and ambient (x=0.25 m, m_{sw}= 0.09 liter/s)

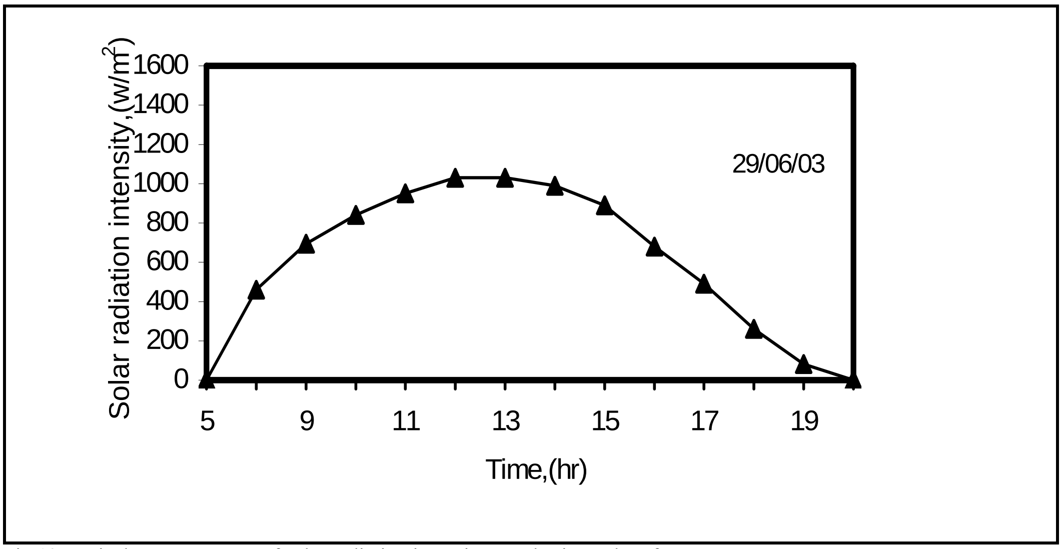

Fig.13 Typical measurements of solar radiation intensity on a horizontal surface

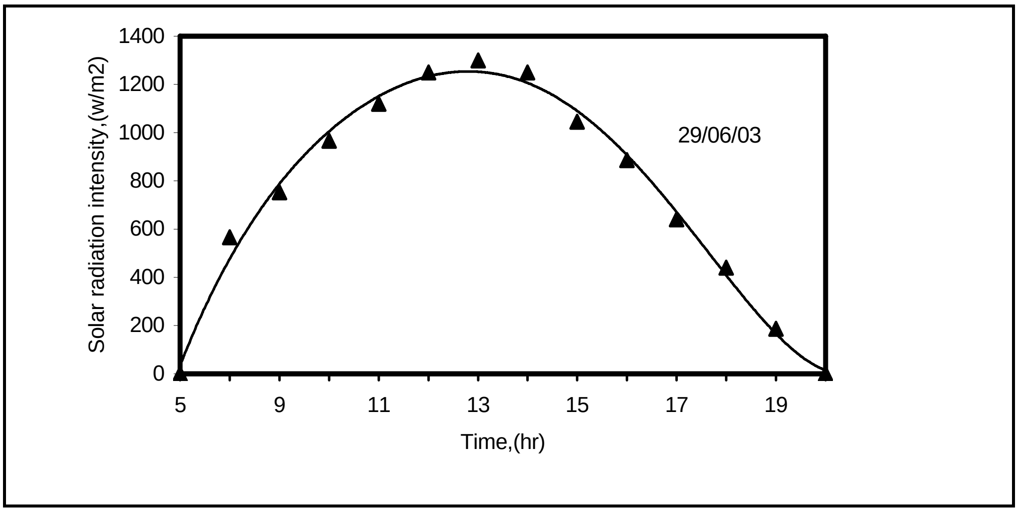

Fig.14 Typical measurements of solar radiation intensity on the central receiver

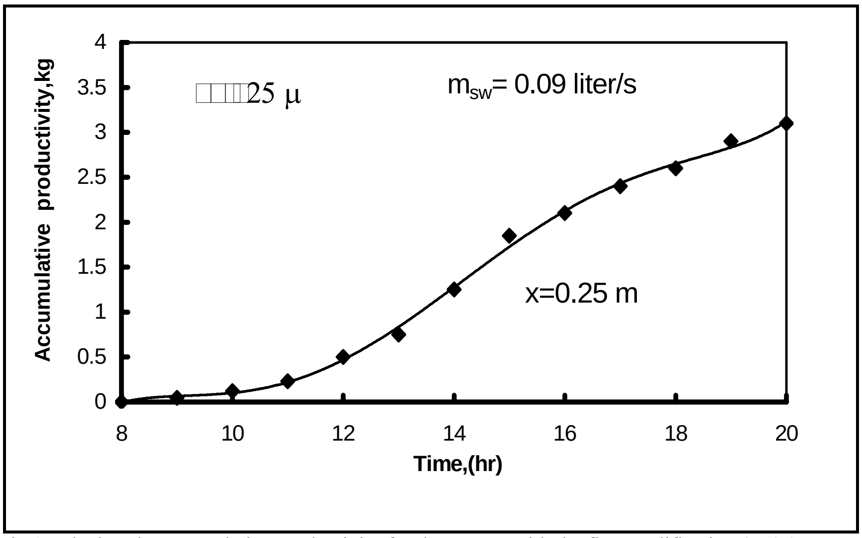

Fig.15 The hourly accumulative productivity for the system with the first modification (x=0.25 m, m_{sw}= 0.09 liter/s)

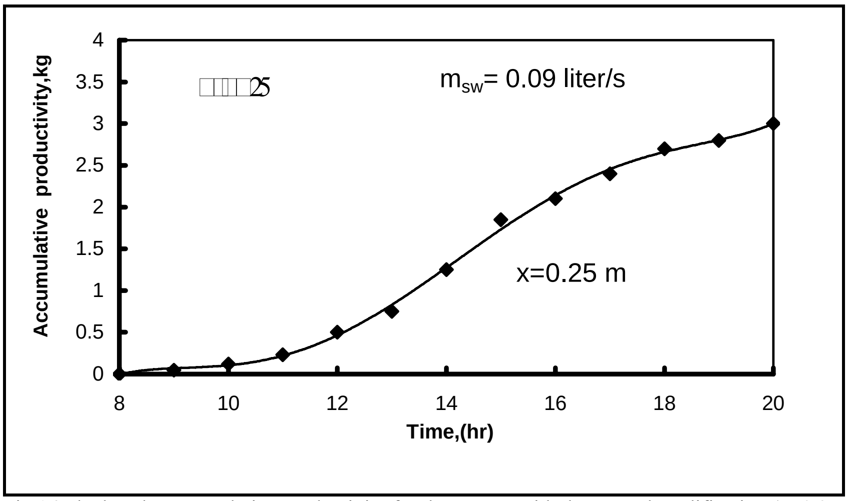

Fig.16 The hourly accumulative productivity for the system with the second modification (x=0.25 m, m_{sw}= 0.09 liter/s)

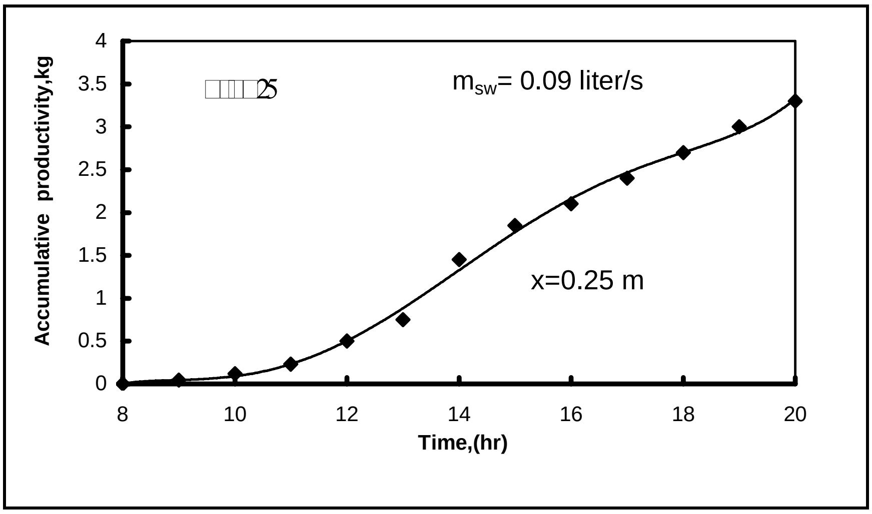

Fig. 17 The hourly accumulative productivity for the system with the two modification (x=0.25 m, m_{sw}= 0.09 liter/s)

دراسة لنظام لتحلية المياه بالطاقة الشمسية يعتمد علي نظرية الترطيب وإزالة الترطيب بواسطة مستقبل شمسي مركزي

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تم في هذا البحث بفضل الله وتوفيقه تصميم واختبار نظام لتحلية مياه البحار والآبار (في الأماكن النائيـة) بالطاقة الشمسية يعمل طبقا لنظرية الترطيب وإزالة الترطيب متعددة التأثير بواسطة مستقبل شمسي مركزي بكليـة الهندسة ببورسعيد– جامعة قناة السويس– مصر.

يتم في هذا النظام تجميع الطاقة الشمسية اللازمة لتبخير الماء المالح عن طريق مـستقبل شمـسي مركـزي يحيط به 28 هليوستات (مرآة) موزعة في ثلاثة دوائر حول مركزه.

غرفة التحلية مقسمة إلي جزأين أحدهما يمثل برج الترطيب (المبخر) والأخر يمثل برج إزالة الترطيـب (مكثف). دورة الهواء في البرجين تتم بواسطة تيارات الحمل الطبيعية. لوحظ أن إنتاجية النظام من الماء المحلي تزداد إذا كان مزرر الماء معلق في منتصف برج الترطيب تماما. النتائج المعملية بينت أنه بزيادة سريان كتلة الماء المالح مـن 0.07 لتر/ ثانية إلي 0.09 لتر/ ثانية تزداد إنتاجية النظام بمقدار 10%.

كذلك أدخل تعديلان علي غرفة التبخير لتحسين الإنتاجية اليومية من الماء المحلـي. تم في التعـديل الأول استخدام غلاف مائي حول برج إزالة الترطيب (المكثف) لزيادة سطح التكثيف وبالتالي زيادة الإنتاجية اليوميـة من الماء المحلي. أما بالنسبة للتعديل الثاني فقد تم تسليط عدد 7 هليوستات بطريقة مباشرة علي أحد جوانب بـرج الترطيب (المبخر) الذي تم تصنيعه من الزجاج لزيادة تسخين الهواء الحامل للبخار وبالتالي زيادة الإنتاجية اليومية من الماء المحلي.

النتائـج المعملـية بينت أن استخـدام التعديل الأول يزيد الإنتاجية اليومية من الماء المحلي بمقدار 15% وأن استخدام التعديل الثاني يزيد الإنتاجية اليومية من الماء المحلي بمقدار 12% وأن استخدام التعديلين معـا يزيـد الإنتاجية اليومية من الماء المحلي بمقدار 22%.