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PERFORMANCE STUDY OF A DESALINATION SYSTEM WITH THERMAL STORAGE

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ABSTRACT

A desalination system has been designed and fabricated. The system consists of a single slope solar distiller coupled with a solar water heating system. The Solar water heating system is working as a thermal storage system. Solar water heating system is used to collect the solar energy during day time and store it in a thermally insulated water tank. This energy is used as a heat source, when required, for the distiller. Another conventional solar distiller, utilizes only the solar energy as a heat source, has been used for comparisons with the modified distiller. Experiments have been carried out during the whole day around the four seasons. Additionally, the effect of adding Zinc Oxide nanoparticles with diameter 23~28 nm to the working fluid of the thermal storage system has been tested. Nanoparticles have been added with two different volume fractions of 0.05% and 0.1%. The results showed that, the enhancement in the productivity of the conventional distiller ranges from 46.8 % to 105.4 % with average 67 % around the year. For the storage system, the daily efficiency was 48% without nanoparticles, and, it is equal to 50.7% and 51.2% for 0.05% and 0.1% volume fractions of nanoparticles, respectively.

الملخص:

تم تصنيع منظومة تقطير تتكون من مقطر شمسى ومنظومة تسخين، حيث تعمل منظومة التسخين كوحدة تخزين للطاقة الشمسية. يتم استخدام منظومة التخزين الحرارى لتجميع الطاقة الشمسية وتخزينها فى صورة طاقة حرارية داخل خزان معزول ، تستخدم هذه الطاقة الحرارية بعد ذلك كمصدر حرارى للمقطر الشمسى ، فيما يعمل مقطر آخر بالصورة التقليدية اعتمادا على الطاقة الشمسية فقط حيث يستخدم للمقارنة بأداء المقطر المعدل فى منظومة التقطير و بالاضافة الى ذلك .تم اضافة مادة اكسيد الزنك النانومترية بقطر 23الى 28 نانومترالى مائع التشغيل فى منظومة التخزين الحرارى ، وذلك بهدف دراسة تأثيرها على اداء منظومه التخزين ، وقد أضيفت هذه المادة بتركيزين مختلفين (بالحجم) هما 0.05% و 0.1% ، أظهرت الدراسة ان استخدام منظومة التخزين الحرارى واسترجاع الطاقة قد بينت زيادة فى انتاجية المقطر الشمسى بنسب تتراوح من 46.8% الى 105.4% ، بمتوسط 67% على مدار العام ، اما عن اضافة مادة اكسيدالزنك النانومترية ، فقد أظهرت النتائج أن هناك تحسن فى كفاءة المنظومة ، وقد زادت كفاءة منظومةالتخزين الحرارى من 48% عند استخدام الماء فقط كمائع تشغيل الى 50.7% و 51.2% عند إضافة اكسيد الزنك بتركيزات 0.05% و 0.1% على التوالى.

KEYWORDS: Solar Distillation; Thermal storage; Water Heating System; Distiller modifications,Nanoparticles

INTRODUCTION

Energy is the foundation on which human civilization rests, for which there is no substitute. One solution to the impending energy shortage is to make much more use of renewable energy sources and technologies. Water has always been earth's most valuable resource. The world's supply of fresh water is running out and its demand has increased dramatically in the last two decades. Desalination is one of mankind's earliest forms of water treatment, and it is still a popular treatment solution throughout the world today.

Solar desalination is a process that utilizes the solar energy (solar radiation) for the separation of salt from water. The most common type of solar desalination systems is the solar distillers. Solar distillers can be categorized into passive solar distillers and active solar distillers in terms of energy supply. In a passive solar distiller, the solar radiation is the only source of energy for raising the water temperature. But, in the active solar distiller an extra thermal energy is supplied to the basin through an external sources to increase the evaporation rate and in turn to improve its productivity. Solar energy is not available all the day as sun is not available at night. Hence, solar energy is considered as unsteady energy source. Thermal energy storage is an essential way to resolve the mismatch. There are three main mechanisms for energy storage: sensible heat storage, latent heat storage and chemical heat storage.

Extensive surveys [1 –6] of literature pertaining to improving distiller performance have been reviewed. Pandey [7] studied the effect of dried forced air bubbling and cooling of glass cover in the performance of solar distiller. Results showed that bubbling of dried ambient air and cooling of glass cover enhanced the productivity by 33.5 and 30.5 %, respectively. Hegazy and Mahmoud [8] studied the effect of using two adjustable flat reflectors on the sides of the distiller. The results indicate that tracking the sun increase the productivity by 25%. Stepped solar distiller with aluminum and cement absorbers without and with auxiliary condenser and flat plate thermo-syphon were designed and tested by Mousa and Abd El-baky [9]. The results indicated the overall efficiency was increased from 50% to more than 65%. Another improvement was presented by Eltawil and Omara [10]. The single slope solar distiller was equipped with a flat plate solar collector, spraying unit, perforated tubes, external condenser and solar air collector. The developed distiller productivity was more than the conventional distiller by 51–148% depending on the type of amendment.

Thermal storage systems depend on converting solar energy into sensible heat in selected materials. Such stored energy is recovered when required. Nafey et al. [11] used black rubber and black gravel as a storage medium. Experimental results obtained that, using black rubber improves productivity by 20 %. Also, using black gravel increases the yield water by 19%. The influence of the injected hot air on the performance of a modified distiller, with phase change material PCM, has been investigated by Kabeel et al. [12]. Paraffin wax was used as PCM. The experimental results showed that, the productivity approximately increased by 52% compared with the conventional distiller. The simple basin solar distiller has been modified using fins, sponges and wicks for augmenting its productivity by Velmurugan et al. [13]. It was found that the productivity has been increased by 29.6%, 15.3% and 45.5% for using wick, sponges and fins respectively. Harris Samuel et al. [14] studied the performance of a conventional solar distiller using different low-cost energy storage materials. From this study, it is observed that the yield of freshwater from the solar distiller was 3.7, 2.7 and 2.2 kg/m^2/dayfor spherical ball salt storage, sponge and without any storage material, respectively. Storage tank system has been integrated with solar distiller by Voropoulos et al. [15]. Storage tank has been kept at a constant temperature using an electrical heater. It has been used as heat source for distiller through of heat exchanger inside distiller. It has been reported that, using any available heat source will be effective. This heat source may be waste heat, conventional sources, electricity, solar collectors, solar pools, etc.

The effect of Al_2O_3 water nanofluid, as working fluid, on the efficiency of a flat-plate solar collector was investigated experimentally by Yousefi et al. [16]. The results showed that, using nanofluid with weight fraction of 0.2% increase the efficiency to 28.3%. An experimental study was performed by Zamzamian et al. [17] to investigate the effect of Cu nanoparticles on the efficiency of a flat plate solar collector. . It was found that by increasing the nanoparticle weight fraction, the efficiency of the collector was improved. Effect of CuO–water nanofluid as the working fluid, on the performance and the efficiency of a flat-plate solar collector has been investigated experimentally by Moghadam and other researchers [18]. The nanofluid with mass flow rate of 1 kg/min increases the collector efficiency by about 21.8%.

From previous review, it could be concluded that, the productivity increases by increasing the difference in temperature between basin and cover. Thermal storage system is necessary to save a lot of the available solar energy at day time to recover it at night. Also, solar water heating system could be used as thermal storage system at no load time. Nanofluid has a great effect on enhancing the heat transfer, as a result it affects well in solar energy applications.

The present work studies the performance of a novel desalination system using solar heating system coupled with basin type solar distiller. The solar heating system is used as a thermal storage system at no load. The performance of novel desalination system is studied experimentally. The thermal storage system is used for collecting solar energy by flat plate collector during the daytime and store it as sensible heat. The collected solar energy is then recovered during night with the aid of a heat exchanger immersed in the water of the distiller. On the other hand, the effect of using Zinc Oxide nanoparticles with the working fluid in thermal storage system is discussed.

EXPERIMENTAL SETUP

An experimental test rig has been designed, fabricated and assembled in the solar energy laboratory, department of Mechanical Power Engineering, Faculty of Engineering, Menofia University, Shebin El-Kom, Egypt at Latitude of 30.56° N and Longitude of 31.01° E. A schematic diagram of the test rig is given in Fig.1. It consists mainly of two identical single slope single basin solar distillers, one is conventional, fig (1.a) and the other is modified. The modified distiller is integrated with a thermal storage system through a copper coil,fig (1.b) immersed in the basin water of the distiller. The set-up has been equipped with suitable instruments for various measurements and for controlling the system operation

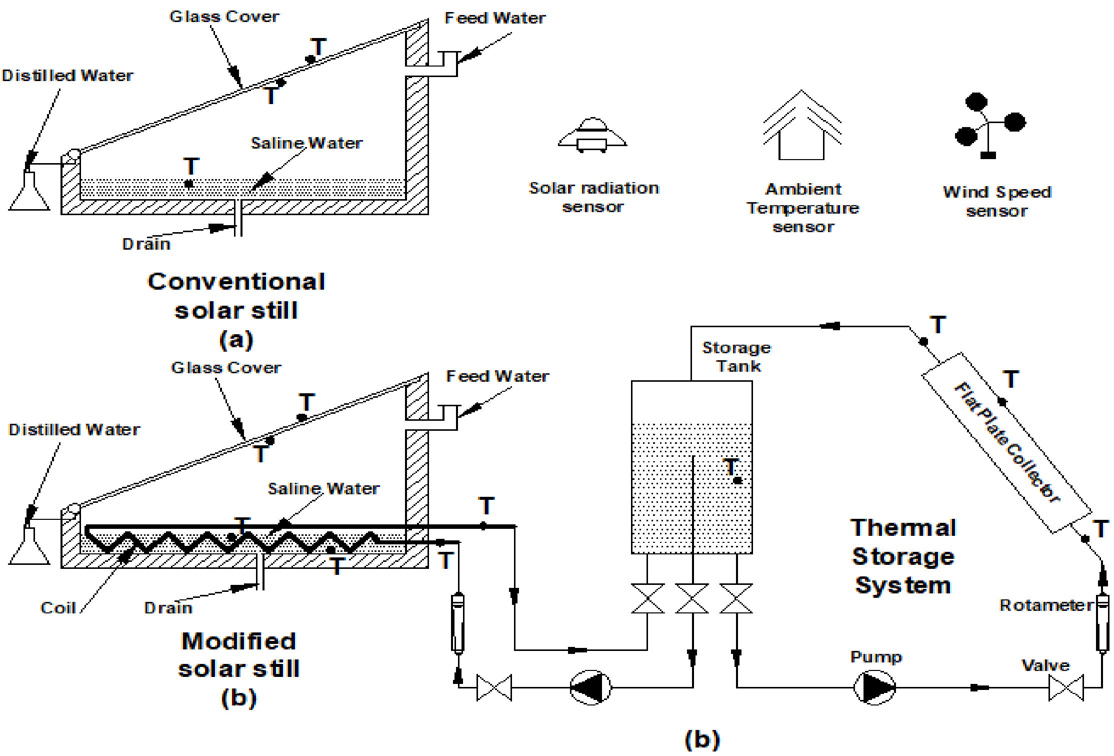

Fig. 1. Layout of the experimental set-up.

Figure 2 presents a schematic diagram of the conventional distiller. The distiller is made from galvanized iron sheets (1.5 mm thick) with a basin area of approximately 1 m^2 (120 cm x 85cm). The wall height on the low-side is 15 cm and the high-side is 70 cm. The whole basin surfaces are internally painted black to increase their absorptivity. Furthermore, the distiller is well thermally insulated with foam pads (5 mm thick, k= 0.02 W/m.K) to reduce the heat loss from the distiller to the ambient. Traditional transparent glass (5 mm thick), with 25 degrees angle of inclination, is used to cover the distiller. Silicon sealant has been used to fill the gaps between the glass cover and still body in order to prevent vapor leakage. The condensed water has been collected using a PVC tube fixed at the lower end of the glass cover. A sight glass has been connected to the distiller in order to indicate the basin water depth. Moreover, the distiller contains feeding and drain tubes, so that the basin water level can be controlled.

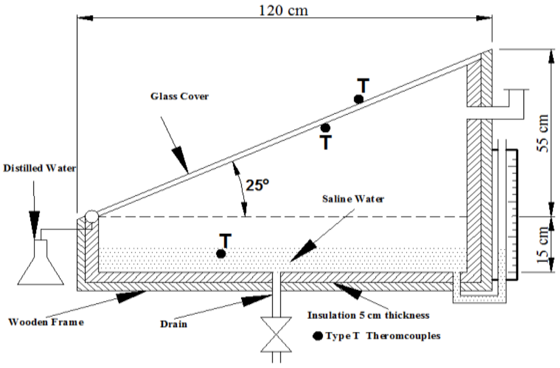

Fig. 2. Schematic diagram of the conventional solar distiller

The thermal storage system consists of a flat plate collector, a storage tank and the supplementary devices as shown in Fig.3.

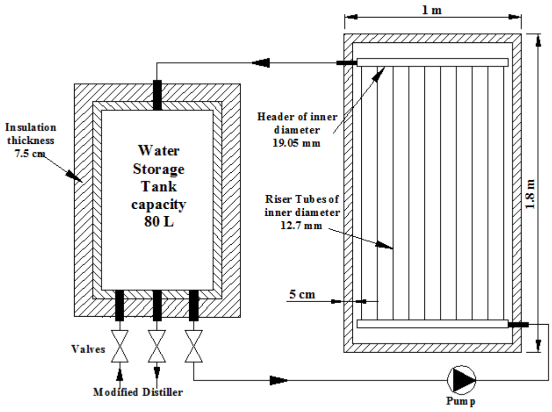

Fig. 3. Schematic diagram of the thermal storage system

The flat plate collector consists of 10 copper riser tubes and two headers, tubes and headers have been integrated together and well welded with a copper sheet. These components have been contained in a box, whose sides and bottom are insulated by foam pads, while its top is covered by a glass sheet. The dimensions of the flat plate collector are summarized in Table 1.

Table 1. Flat plate collector dimensions

Specifications	Dimensions	Units
Size of Collector	Width=1, length=1.8, depth=0.07	**m**
Net absorber area	1.53	**m^2**
Header diameter	19.05	**mm**
Riser Tube diameter	12.7	**mm**
Cover plate thickness	5	**mm**
Edge thickness	50	**mm**
Back thickness	50	**mm**
Tilt angle	20	**degree**

A Tank of 80 liter capacity has been coupled with the solar collector. The storage tank has been insulated by glass wool insulation to decrease thermal energy losses. All connections, piping and hosing are insulated. A 0.5 HP pump is used to circulate the water inside the collector and the tank to ensure a known and a constant flow rate of 2 LPM.

Table 2 presents the ranges and uncertainties of the measuring devices.

Table 2 Instruments ranges and uncertainties

Instrument	Range	Uncertainty
Pyranometer	0-2000 W/m^2	$\pm$ 10 W/m^2
Thermo Anemometer	0.4-25 m/s	$\pm$ 0.05 m/s
Thermocouples type T	-200-200 °C	$\pm$ 1 °C
Flow meter	0.5-8.5 L/min	$\pm$0.12 L/min

Nanofluid Preparation

Zinc Oxide nanoparticles have been successfully synthesized through a solid-state thermal decomposition method for Zinc Acetate ($Zn(CH_3COO)_2 \cdot 2H_2O$) as reviewed in [19 – 21]. The preparation of nanoparticles has been performed at strength of materials and tests laboratory, department of Mechanical Production and Design Engineering, Faculty of Engineering, Menofia University, Egypt. XRD test of the synthesized Zinc Oxide has been carried out in the nanotechnology laboratory, Agriculture Research Center, Cairo, Egypt. The results obtained from XRD test are shown in Fig. 4. Extremely broaden reflection peaks are observed, which is an indication of the fine nature of particles, obtained from Zinc Oxide nanoparticles. The crystalline diameter (Dc) of ZnO nanoparticles can be calculated using the Scherer equation [20]:

$$D_c = k_f \lambda / \beta_n \cos \theta_n$$

where β is the breadth of the observed diffraction line at its half maximum intensity, k_f is the so-called shape factor which usually takes a value of about 0.9, and λ is the wavelength of X-ray source used in XRD.The crystalline diameter of Zinc Oxide nanoparticles has be calculated using the Scherer equation [20] and was equal 28 nm.

TEM test of the synthesized ZnO has been carried out in the nanotechnology laboratory, Faculty of Science, Menoufia University, EGYPT. TEM images of the synthesized ZnO are shown in Fig.5. From this figure, it was observed that the particle size is in the range of 12-60 nm with average particle size of 23 nm.

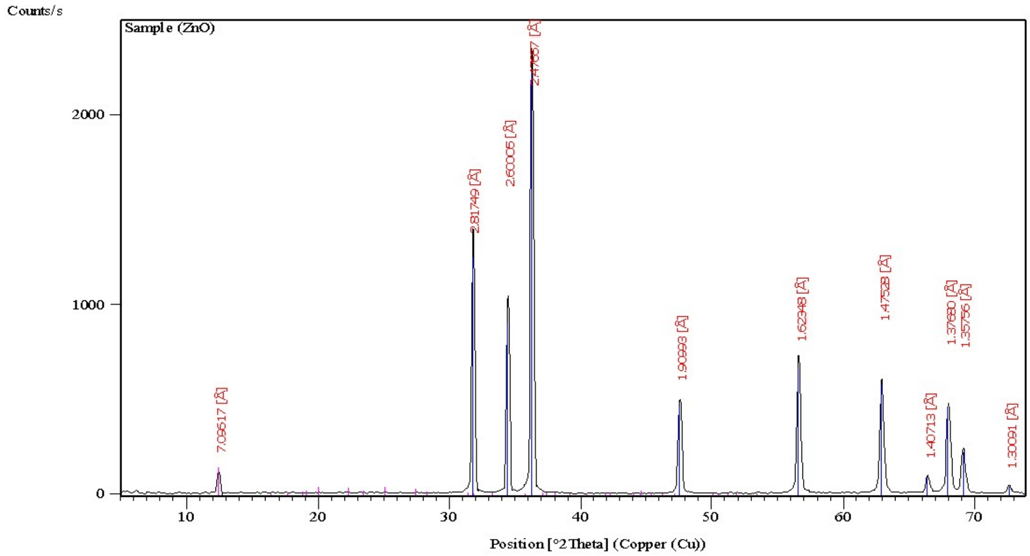

Fig. 4. XRD patterns of prepared ZnO nanoparticles

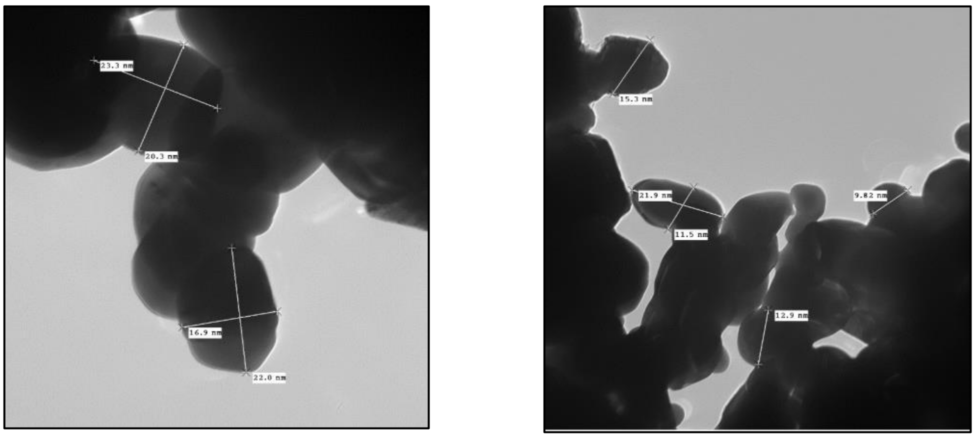

Fig. 5. TEM images of prepared ZnO nanoparticles.

EXPERIMENTAL PROCEDURE

The measurements have been recorded throughout the day and night (24 hours) once every month from August 2015 to August 2016. The solar radiation and ambient temperature have been measured. For the distillers; basin water, inner and outer glass temperatures have been measured. Finally, for thermal storage system; absorber plate, inlet and outlet, glass cover temperatures of flat plate collector and thermal storage tank temperature have been also measured. Measurements have been recorded every 30 min. However, the productivity has been measured every one hour. The depth of basin water has been kept constant during the experiments at 3cm.

At the beginning of the experiment, the two distillers as conventional distillers and the thermal storage system stores the solar energy as a sensible heat in the water inside the tank. When the temperature of the modified distiller decreases in two successive readings, the thermal storage system is stopped manually and the recovery system is started to recover the stored energy throughout the rest of the day.

Experimental Results

A-Desalination System Performance

Figure 6 presents the variation of global solar intensity during the daytime with the local time. It is observed that, the global solar intensity increases rapidly in the morning and attains its maximum value at the noon, then it decreases until approaching zero value at sunset. Such behavior is noticed during the four seasons. However, the maximum global solar radiation is found to be around 950 W/m^2 in summer season. Radiation fluctuations are noticed in some days due to some clouds.

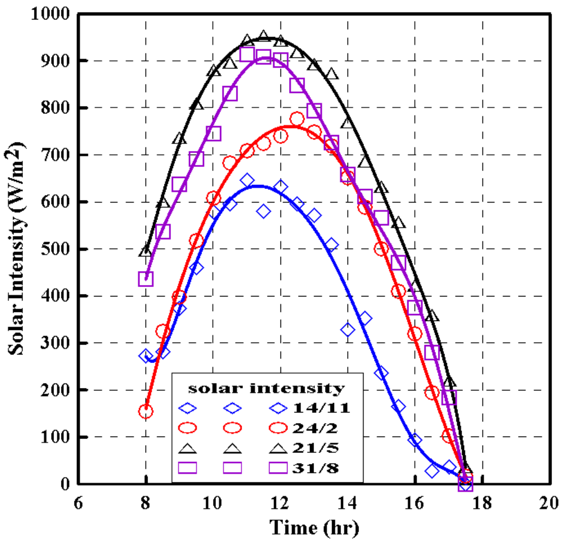

Fig. 6 Variation of global solar intensity along the day

For the flat plate collector, the variation of temperatures at inlet, outlet, cover, absorber and ambient are presented in Fig. 7. These temperatures are recorded during the operating period of thermal storage system. This period starting at 8:00 AM and ending at 4:00 PM. It is seen that, the temperature difference between inlet and outlet is approximately constant with time till around 1:00 P.M. This means that the amount of heat added to the recirculated water is constant, in spite of the increase in solar radiation. Part of the solar radiation is stored in the absorber plate and other construction materials. Also, as the absorber temperature increases, the heat losses become larger, causing a smaller gain in useful energy

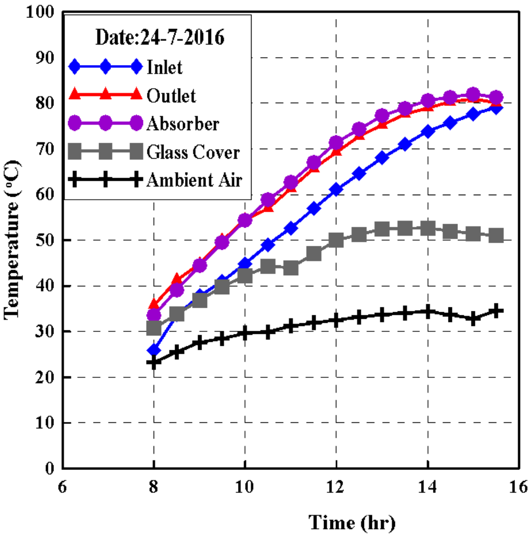

Fig. 7 Measured temperatures of flat plate solar collector

Figure 8 illustrates that the storage tank temperature increases with the increase of solar intensity, reaching its maximum value at 4:00 P.M. At this time, the hot water drawn from the storage tank is used as a heat supply to the modified solar still to start the recovery process of stored energy. As a result, the tank temperature begins to decrease. Moreover, the storage tank maximum temperature varies around the year following the solar intensity variation. Specifically; this temperature reaches its lower value of around 48 °C in December while, its higher value of around 80 °C is achieved in summer season.

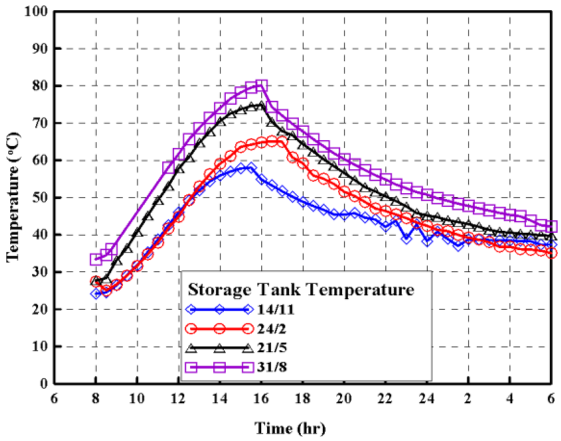

Fig. 8 Thermal storage tank temperatures

Comparisons of basin saline water temperature between conventional and modified distillers are shown in Fig. 9 and Fig. 10. The temperatures of conventional distillers follow the variation in solar intensity. However, the modified distiller temperatures have the same behavior of the conventional sill but exhibit a sudden increase when the recovery system is started. This increase in temperatures is followed by an almost constant difference in temperatures for the rest of the day.

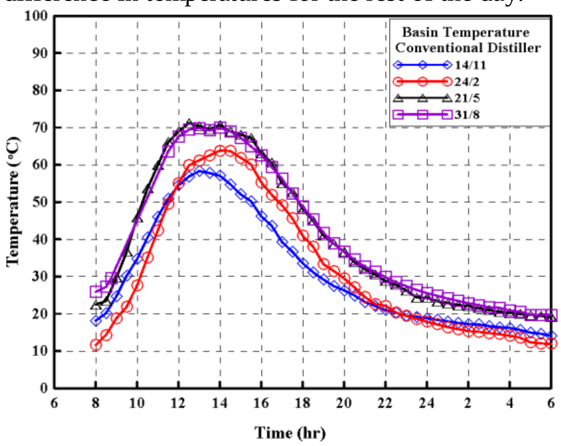

Fig. 9 Basin temperatures of conventional distiller

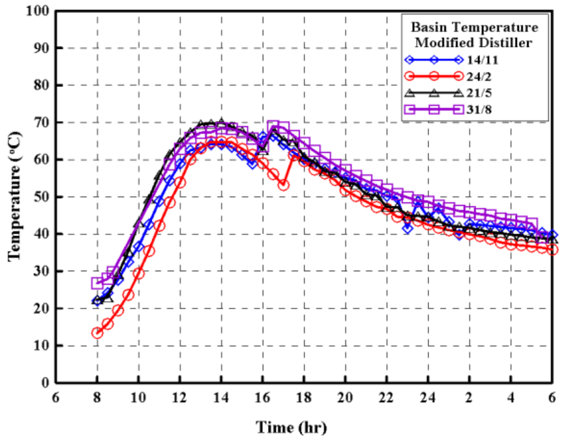

Fig. 10 Basin temperatures of modified distiller

Figure 11 and 12 show comparisons between the productivity of the conventional and the modified distillers. From these figures, it is observed that the productivity of both distillers varies following the solar intensity changes during the day as well as the whole year. Before the recovery process, it can be noticed that the conventional distiller productivity is more than that of the modified one. This difference occurs in spite of the same geometrical and operating conditions. The heat absorbed in the copper coil in the modified distiller is the main reason for this difference. It is also seen that; the modified distiller productivity is much higher than that of the conventional one during the operation of recovery system. This is attributed to the higher evaporation rate from the modified distiller basin water according to the higher basin water temperature compared to that in the conventional distiller. In addition, Fig. 13 and 14 show the change in the daily accumulated productivity. Figures show that there is an increase in the modified distiller in general. For instance, it changes from 1.9 to 3.7 and 3.9 to 7 liters in November and August, respectively.

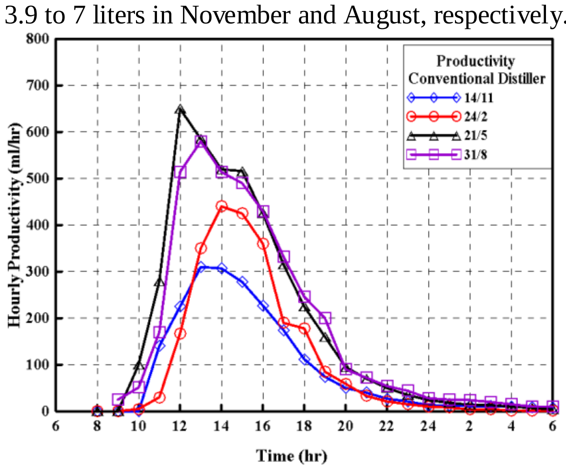

Fig. 11 Productivity of conventional distiller

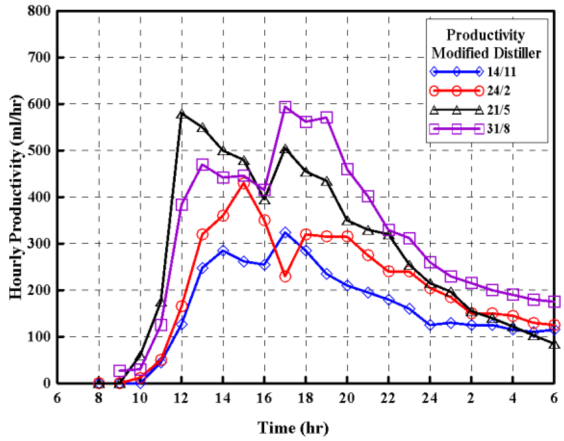

Fig. 12 Productivity of modified distiller

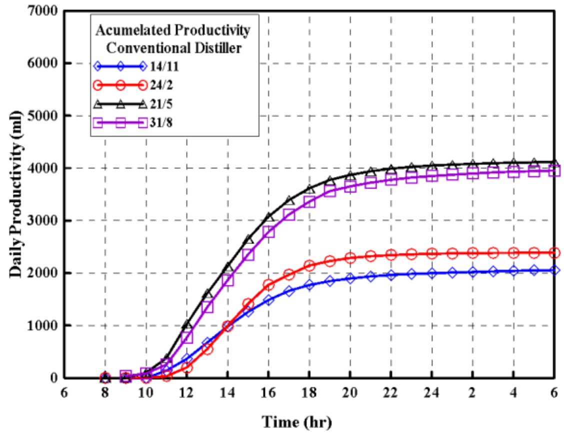

Fig. 13 Accumulated productivities of conventional distiller

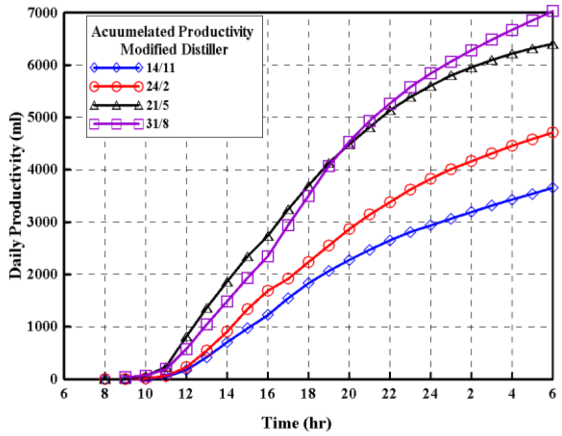

Fig. 14 Accumulated productivities of modified distiller

In order to provide a more useful representation of the productivity around the whole year, the average accumulated productivity of the conventional and modified distillers have been specified for each month, as demonstrated in Fig 15. It is clear from this figure that, the daily productivity of both distillers have their lowest values in December, followed by a gradual increase till April. Such change is constant during the period from April to August. Overall, there is an enhancement in the productivity of the conventional distiller ranges from 46.8 % to 105.4 % in April and November, respectively. It is also observed that the percentage productivity enhancement is lower in Spring and Summer seasons compared to the other two seasons as shown in Fig 16. This is due to the higher ambient temperature during night in Spring and Summer. Increasing the ambient temperature tends to lowering water condensation over the glass cover which in turn reduces the productivity during the recovery process. Finally, there is an average increase in the productivity by 67 % around all the year.

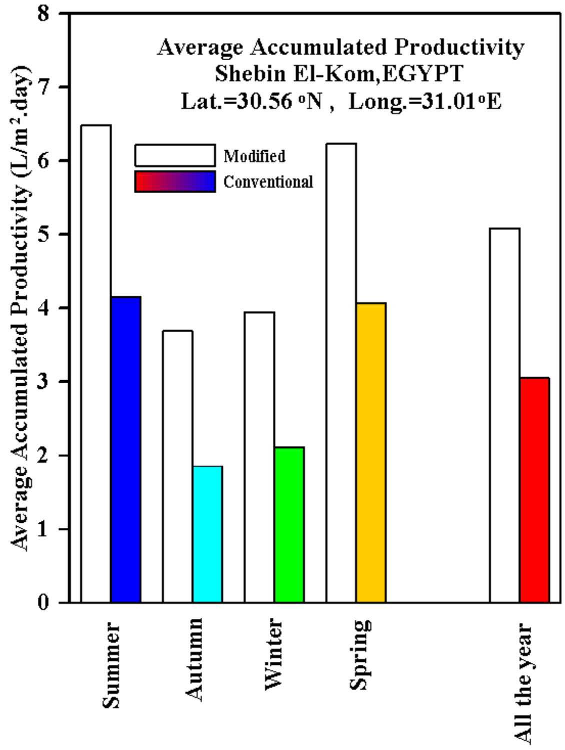

Fig. 16 Average seasonal and yearly productivity

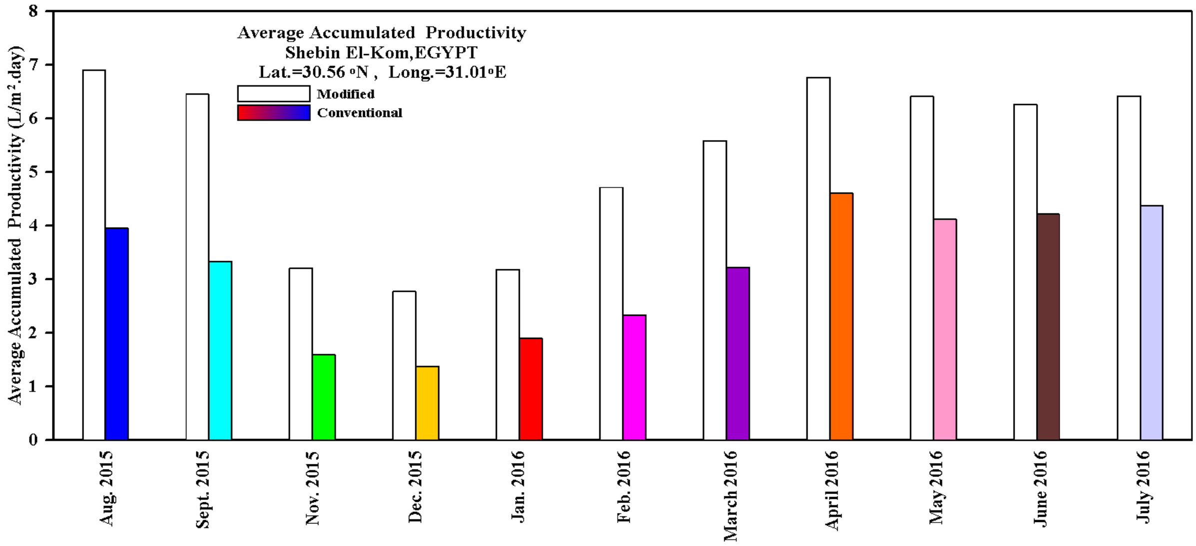

Fig. 15 Average monthly productivity

B-Effect of using Nanofluid

The effect of using Zinc Oxide nanoparticles with the working fluid in the thermal storage system presented in the following section. The following comparisons have been performed for the pure water as well as two volume fractions of nanoparticles equal 0.5 % and 0.1 %, respectively. These experiments have been carried out during a short period of time (3 days of a week) in order to guarantee the roughly same weather conditions.

It is known that, the efficiency of the thermal energy storage system is dependent on the incident solar energy and the amount of heat gained by the working fluid. The stored energy Q and rate of stored energy $\dot{Q}$ can be calculated using the following equations;

$$Q = m_w \, c_{pw} \, (T_{Tank} - T_i)$$

$$\dot{Q} = \frac{m_w \, c_{pw} \, \Delta T}{t}$$

where m_w is the mass of the contained water inside the tank, c_p is the water heat capacity, ΔT is the water temperature difference during the period t (30 min) of measuring the incident solar radiation and T_i is the initial tank temperature.

Storage efficiency defined as, the ratio between the stored energy rate in the water tank ($\dot{Q}$) and the incident solar energy (I_{FPC}) on the glazing surface of the flat plate collector during a certain period. Therefore, this efficiency is given as;

$$\eta_{storage} = \frac{\dot{Q}}{I_{FPC}\, A_{FPC}}$$

where, A_{FPC} is the area of flat plate and

Figure 17 demonstrates the hourly efficiency of the thermal storage system for the three conditions. The addition of the Nano material to the storage working fluid enhances the system efficiency around the time of operation. Furthermore, the higher the volume fraction, the higher system efficiency obtained for the tested concentrations. Surprisingly, the system efficiency for the higher volume fraction of 0.1 % is smaller than that of the other volume fraction and the pure water at the beginning of the thermal storage process. This behavior may be attributed to the heat absorbed by the nanoparticles from the water at the beginning of the heating process. Therefore, the increasing rate of the water temperature is slower for the higher concentration of the nanomaterial. After that, the impact of the nanomaterial begins to be effective, causing slight increase of the temperature.

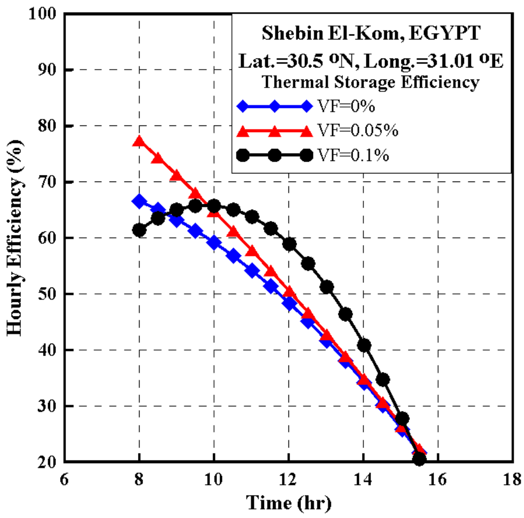

Fig. 17. Variation of hourly efficiency of thermal storage system for different volume fractions of nanoparticles

Finally, employing nanomaterial with the thermal storage working fluid records an improvement in the daily efficiency, as presented in Fig. 18. The amount of stored heat in the water tank throughout the whole heating process is also enhanced by using nanofluid.

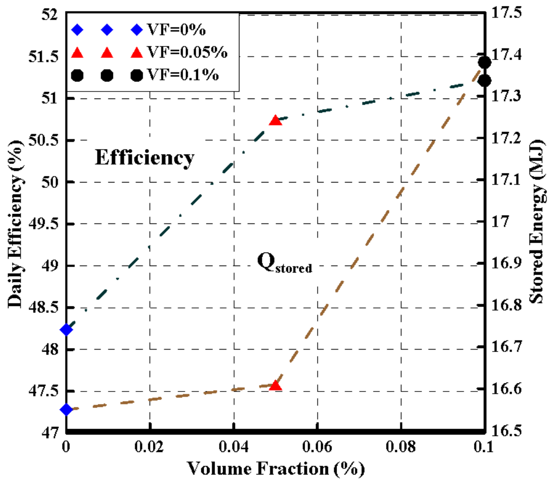

Fig. 18. Effect of nanoparticles volume fraction on the daily efficiency and stored heat in the storage tank.

The obtained results of the efficiency are qualitatively consistent with the measurements of Otanicar et.al. [22] as shown in Fig.19. Also, these results are in considrable agreement in tendency with the numerical published work of Tyagi et.al. [23] as presented in Fig.20.

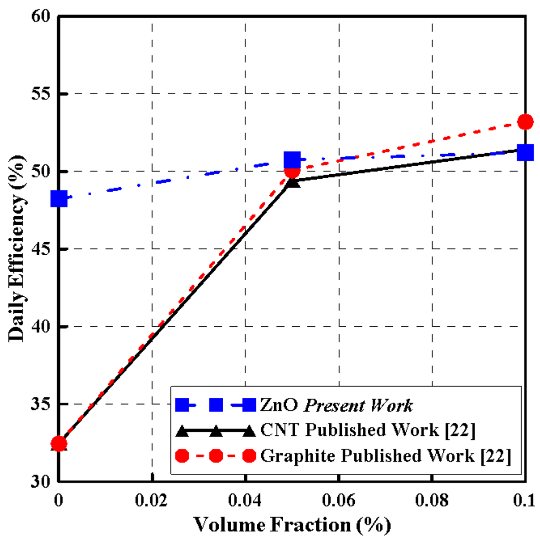

Fig. 19 Present experimental data of daily efficiency and data of Otanicar [22]

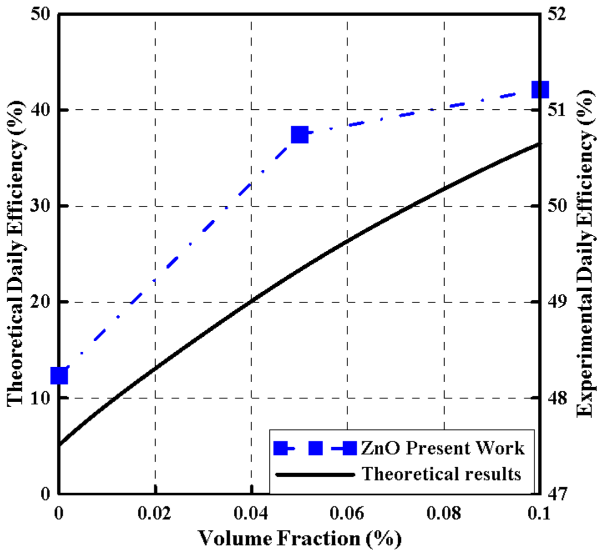

Fig. 20 Present experimental data of daily efficiency and theoretical of Tyagi et al [23]

Conclusions

The present work investigates experimentally the performance of a novel desalination system. Such system depending on coupling single slope solar distiller with solar heating system working as thermal storage system at no load. The thermal storage system is used to collect the solar energy during day time and store it in a thermally insulated tank. Such energy is used as a heat source, when required, for the distiller. Besides, the performance of thermal storage system only examined with adding ZnO nanparticles to working fluid for only three days with different volume fractions. It is observed that using the recovery system causes an increase in the Productivity of the distiller. The productivity enhancement of the conventional distiller ranges from 46.8 % to 105.4 % in April and November, respectively, with average 67 % around the year. It is also observed that the percentage productivity enhancement is lower in spring and summer seasons compared with the other two seasons. Besides, the daily efficiency of the thermal storage system increased from 48% for pure water to 50.7% and 51.2% for 0.05% and 0.1% volume fractions of ZnO nanoparticles, respectively.

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