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Enhancing Solar Still Productivity: Use of Nanomaterials

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Abstract: Much care is being given for the issue of sustainable development in the last few years. Among these efforts, researchers are giving much interest to saving water resources, energy conservation and protecting environment from pollution resulting from the use of fossil fuel. The present study is an investigation for the effects of operational and design parameters on the performance of basin type passive solar stills. Two types of nanomaterials are used for enhancing still productivity. The materials tested are nano-ZnO and nano-TiO2. Besides, experiments are run on TiO2 particles and on a reference still with no materials added except saline water. This gave a chance to investigate the effect, on still productivity, of adding an energy absorbing material, the effect of having this material in a nanoform and a comparison between the performances of different materials. The parameters of ambient temperature, basin temperature, glass temperature and solar intensity are studied. A total productivity amounting to 1645ml, 1560ml and 1115ml was obtained per day from stills having nano-ZnO, nano-TiO2 or TiO2 particles (0.6 g/l), respectively. The still efficiency is calculated to be 34.93%, 48.87% and 51.53% when TiO2, TiO2 NPs and ZnO NPs are used, respectively. Thus, ZnO showed the best productivity, followed by TiO2 and finally by TiO2 particles.

Keywords: Still, solar, nanomaterial (NM), productivity, enhancing

1. INTRODUCTION

The process of solar distillation of salt water is one of the most important methods for obtaining pure water with a simple and inexpensive technology [1-3]. Solar distillation is recently considered the most important technology for solving water problems in the world [4-6]. There are many ways to harness energy, and this is what research strives for [7-10]. Solar energy in all cases (heat cooking, reflective lenses and cells) saves more than 10,000 times the fuel energy used by almost all of humanity [11, 12]. The traditional solar distillation unit is one of the simplest types, and the amount of water produced ranges from 1 to 4 liters/m2/day) with a thermal efficiency of up to 50% [13]. Efficiency of solar distillation depends on several factors, including the design of the distillery and others related to weather conditions such as ambient temperature and the amount of solar radiation [14, 15]. Solar stills are divided into two main classes; active solar stills and passive solar stills [16, 17].

Some studies discussed adding external elements to the solar stills such as solar collectors or concentrators [18]. However, recent studies have focused on using nanoparticles such as graphite, CuO, SiO2, TiO2 and Al2O3 nanofluids on the solar collector to improve its performance [19-22].

A review paper [23] discussed energy exchange and energy storage materials including nano embodied PCMs, nano fluids and nanoparticles, nanostructures with efficient steam generation and sensible heat storage materials for solar desalination.

Another review [24] focused on recent enhancement techniques aiming at boosting solar still performance by incorporating non-metallic nanofluids into the base fluid. The nanomaterials examined in this review include Al2O3, CuO, ZnO, and TiO2. Several studies found that adding Al2O3 in a solar-still desalination system resulted in an increase in distillate yield, better efficiency, reduced energy consumption, reduced thermal loss, and better productivity.

Another group [25] worked on a hybrid nanofluid by using a two-step method with cerium oxide (CeO2) nanoparticles and multi-walled carbon nanotubes (MWCNTs) in a ratio of 80:20. The modified still (MS) achieved a maximum production of 1430 ml compared to the conventional still's (CS) maximum output of 920 ml. The levels of TDS in the MS and CS were 96.38% and 92.55% lower than those in saline water.

The characteristic features of nanoparticles and the recent developments, in the usage of nano-based PCM and pure nanoparticles as a thermal storage medium in solar stills, were discussed in a review paper [26]. It showed the use of pure nanoparticles and nanoparticles integrated with PCM; which helps in increasing the PCM

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thermal conductivity when compared to base fluids and has been chosen as the best suitable technique for increasing still productivity.

A review paper published in 2021 [27] found that the efficiency and daily productivity of the solar still was increased by using nanoparticles in it. Another review [28] investigated experimentally the impact of combined utilization of copper oxide (CuO) nanoparticles, both in thermal energy storage unit and absorber coating, on the performance of a single-slope solar still. Experimental results showed that combined employing nanoparticles upgraded accumulated productivity by 26.77% in comparison to conventional solar still.

The recent developments for achieving high-performance solar stills by micro/nano-materials were discussed [29]. The reviewed studies have indicated that the enhancement of productivity and efficiency depends on many factors, such as particles concentration, materials type, systems configurations and solar intensity.

A recent study [30] discussed the novelty of basic concepts such as working principle of nanofluid, heat transfer in nanofluid and different preparation methods. An important result is that thermal conductivity of nanofluids is proportional to nanoparticles concentration to a certain limit. So, each nanoparticle has its optimum concentration where thermal conductivity is maximum in order to give maximum yield of pure water.

Some researchers [31] synthesized a novel multilayered 2-D MXene from 3-D MAX phase as a coating material for the solar still to improve its performance. Higher MXene loading significantly augmented the thermal conductivity and solar absorptivity of the turpentine oil/black paint solution. The 0.1 wt% MXene coated absorber provided a higher heat transfer rate from the absorber to the water, leading to a 6% increase in water temperature and a total water yield of 2.07 kg. The average energy efficiency of the SS with 0.1 wt% MXene in the absorber black paint coating was 36.31%.

A study was made [32] with the main goal of looking at the most important new developments in desalination nanotechnology with respect to energy. Some conclusions and suggestions for future research are made; based on the progress made and the problems that still need to be solved.

Multiple innovative materials for efficient water production by solar stills have been invetsigated in the literature [33]. This includes a focus on innovative materials including nanomaterials, nanofluids, nanoparticles-based phase change materials (PCMs), composite PCMs, PCMs with porous materials and PCMs with heat pipes. The review's outcomes identify that advanced energy storage materials substantially influence the enhancement of solar still productivity as compared to conventional solar stills. The productivity of solar desalination can also be improved by utilizing PCM/porous materials, with results indicating solar still water productivity to be enhanced by between 40 and 70%.

A study evaluated the performance of an integrated model of conventional solar still (CSS), flat plate collector (FPC) and parabolic trough collector (PTC) for the production of potable water using ZnO, Al_2O_3, TiO_2 and CNT nanomaterials [34]. The experimental results revealed that the highest water production rate of 0.478 $lm^{-2}\,h^{-1}$ (LMH) was in case of integrated system consisting of CSS, FPC and PTC using CNT based nanofluid, which was 153% higher than that of CSS without nanoparticles. The water yield of the integrated system was 0.458, 0.466 and 0.466 LMH for ZnO, TiO_2 and Al_2O_3 nanofluids, respectively at 0.1 wt% concentration.

The present study aims to improve the yield of solar distillers by using different nanomaterials. The materials examined are TiO_2 particles, TiO_2 nanoparticles and ZnO nanoparticles. The effects of their addition as well as a comparative study between the different materials in terms of their productivity and efficiency are presented in the study.

2. Materials and Method:

I. Materials:

Analytical grade materials are used in the present study and it were obtained from Sigma Aldrich, as follows: sodium chloride for the preparation of salt water with 2000ppm salt concentration, titanium oxide TiO_2 with a purity of 94%, titanium oxide nanoparticles (99.5% trace metals basis, particle size 21 nm (TEM), s urface area 35-65 m^2/g (BET), density 4.26 g/ml at 25°C), zinc oxide nanoparticles (ZnO NPs) (particle size: less than 100 nm) and anatase TiO_2 catalyst with specifications (fine white powder, particle size: 0.05 mm and density: 0.94 g/cm^3).

II. Method

A. Experimental setup:

The experimental setup consists of four basin type solar stills with stainless steel basins and an area of 1 m^2. It is covered with a 0.003 m thick glass pane and its bottom is blackened to absorb the maximum solar radiation. The water distillate is collected on the lower side of the glass cover, moved through a water passage and ultimately collected in a graduated cylinder. All experiments are performed in batch mode and at room

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temperature. Stills are fitted with thermometers to measure: basin temperature, vapor temperature and inside glass cover temperature.

B. Solar desalination experiments:

Equal volumes of saline water are prepared and an energy storage material (TiO_2 particles, TiO_2 NP or ZnO Np) is added to each, mixed well and poured into one solar still. The fourth still is being used as a reference still for the object of comparison.

The hourly distillation rate (ml/h/m2), solar intensity (W/m2), and temperatures (basin temperature, glass cover temperature, vapor temperature, and ambient temperature) are recorded (OC). The internal glass temperature and the water temperature in the basin were measured with the digital multipoint meter (Fluke) "2166A" with thermocouples. Ambient temperature was measured using a standard thermometer. The volume of distillate was measured by collecting it in 1000 ml graduated cylinders, and solar intensity was measured using the "Eppley Black and White Pyranometer", model 8-48 with sensitivity (conversion factor) of 8 µV/Wmµ. The hourly collected distillate from each still is measured, recorded and used later on for calculating daily still productivity and efficiency of different stills. Temperatures readings are also recorded hourly and its change with time is plotted together with the values of solar intensity.

3. Results and discussion:

All experiments were conducted in the Faculty of Engineering, Minia University, Egypt (30.45' east longitude), in 2021, on several consecutive days between 9 am and 6 pm during the summer months (July and August 2021).

I. Effect of adding TiO2 particles in the still basin:

Two solar stills with one basin and one inclined surface are used. TiO2 (800 ppm) was added to one still, while the other still served as a reference.

Fig. 1 shows the hourly productivity of the reference still and the solar still with TiO2. It can be seen that the effect of adding TiO2 is more evident around noon due to the high solar intensity and the consequent activation of the photo thermal properties of TiO2 [35, 36].

When thermally activated, TiO2 acts as energy sink absorbing solar energy and transferring it to the basin water thus heating it. The daily productivity of a single-basin solar still without TiO2 addition was 870 ml/m2 /day, and with TiO2 addition was 1245 ml/m2 /day. Thus, the addition of TiO2 increases the productivity of the distillation system by 43.1%. These productivity values correspond to a system efficiency of 28% for the reference still and 39% for the still with TiO2.

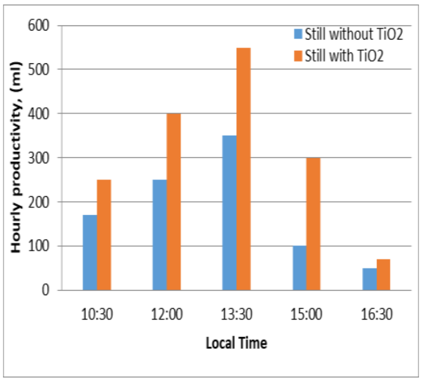

Fig. 1: Effect of adding TiO_2 on hourly still productivity

A. Effect of temperature gradient (T_b-Tg):

The temperature gradient between basin temperature (Tb) and the temperature of the inner glass cover (Tg) represents the driving force for the progress of distillate production. The values of the temperature gradient for the reference distillation unit and for the distillation unit with TiO2 are shown in Fig. 2. It is clear that the still with TiO2 has higher values for the temperature gradient, which leads to an increase in productivity compared to the reference still [25]. It is interesting to note that the temperature gradient is negative at the beginning of the day. This could be due to the glass cover being exposed to solar radiation at the beginning of the day, heating up to a higher temperature than the temperature of the basin, resulting in a negative temperature gradient [38]. As time progresses, the pool heats up; increasing its temperature, resulting in positive temperature gradient values. Therefore, no yield was obtained at the beginning of the day when the temperature gradient was negative.

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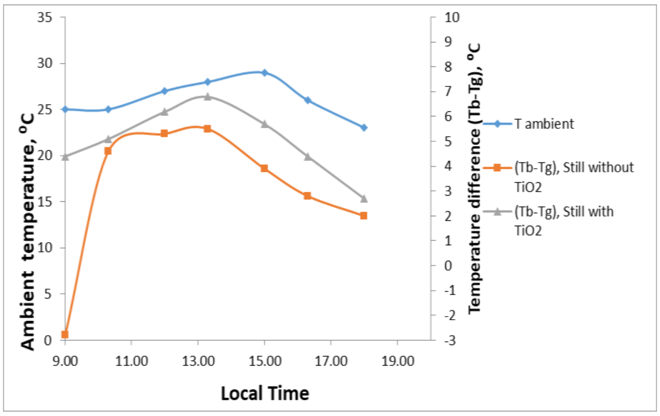

Fig. 2: Change of temperature gradien (Tb-Tg) with time for stills with and without TiO_2

B. Effect of Solar Intensity (SI):

The effect of change in solar intensity during the day on the hourly productivity of the distillery is shown in Fig. 3. From this figure, it can be seen that both the SI curve and the distillers' productivity curve have the same trend, i.e., lower values at the beginning and end of the day and maximum values at midday. Thus, distillation productivity is proportional to solar intensity [39]. The maximum hourly productivity of the stills with and without TiO2 is 550 and 340 ml/h/m2, respectively, with a maximum solar intensity value of 690 W/m2 at solar noon.

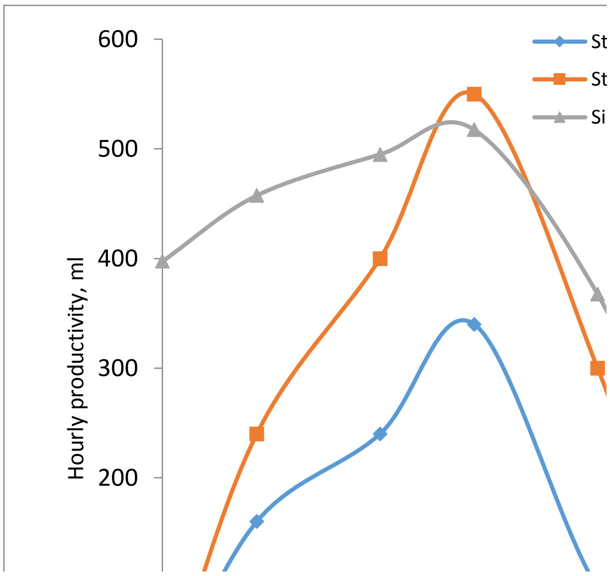

Fig. 3: Effect of Solar Intensity (SI) on hourly still productivity

II. Effect of using Nano particles on solar still productivity:

A. Effect of using TiO_2 and Nano TiO_2:

In the present experiments, the effect of using TiO_2 as nanoparticles on solar still performance is experimentally investigated. Two solar stills were used; TiO_2 particles were added to the salt water in one still and nano-TiO_2 was used in the other still. The same catalyst concentration is used in both stills (0.15 wt%). Fig. 4 shows the hourly productivity of both stills. It is clear that the use of TiO_2 nanoparticles leads to an increase in solar still performance compared to solar still with TiO_2 particles. This is due to the photo thermal activation of TiO_2 NP when exposed to solar radiation, an action which results in solar energy being stored in the Nano material, and is consequently transferred to the basin water causing an elevation in its temperature and enhancing its evaporation.

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Fig. 4: shows that the effect of using nanomaterials to increase the productivity of stills becomes more pronounced around noon, and that this effect diminishes as we approach the sunset hour. A maximum increase of 30.1% in distillation productivity is achieved at 13:00 by using nano-TiO_2.

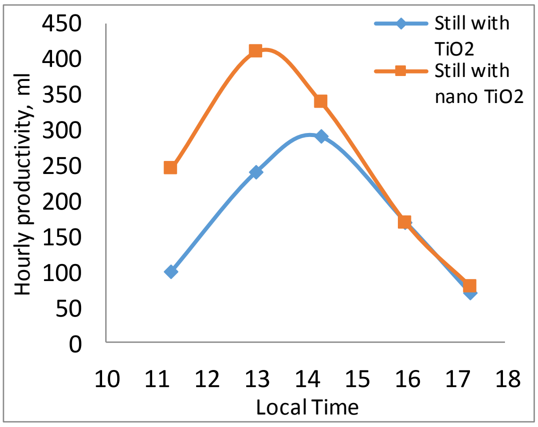

Fig. 4. Effect of using TiO_2 NPs on hourly still productivity

Moreover, the pool temperature of the still with nano-TiO2 is higher than that of the still with TiO2 particles, as shown in Fig. 5. This is related to the photo thermal properties of TiO2, which are supported by the higher solar intensity at noon [40]. This increase in pool temperature is one explanation for the higher productivity of stills with TiO2 NPs [41].

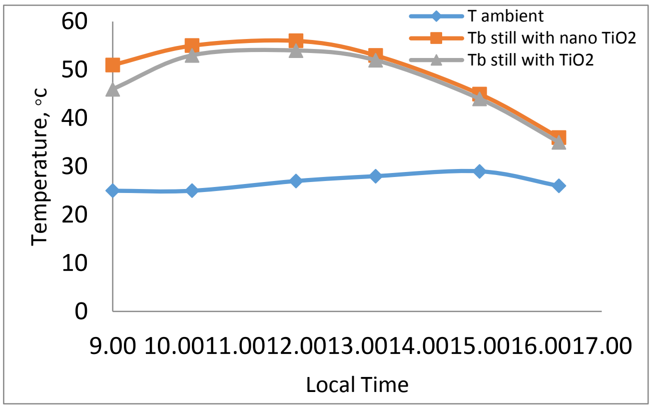

Fig. 5: Change of basin temperature with the addition of TiO_2 NPs

Figure 6 shows the variation of hourly distillation power with solar intensity for stills with TiO2 and TiO2 NPs. This figure shows that all curves have almost the same trend, i.e., low values at the beginning of the day and at sunset and maximum values at solar noon. The positive effect of the addition of TiO2 in the form of nanoparticles is more evident in the morning region and reaches its maximum value at noontime. This is due to the photocatalytic effect of TiO2 particles, which becomes more evident in the presence of sunlight [42, 43]. The maximum hourly distillation productivity of 410 ml/h/m2 is obtained for the distillation unit with TiO2 NPs compared to 290 ml/h/m2 for the distillation unit with TiO2 particles; both at a maximum solar intensity of 710 W/m2 at solar noon.

The daily productivity of the stills with TiO2 and TiO2 NPs is shown in Fig. 7 (with values of 1570 and 920 ml/h/m2 for still with TiO2 NPs and still with TiO2, respectively). Thus, the daily productivity of the stills is increased by 70.7% by using TiO2 NPs.

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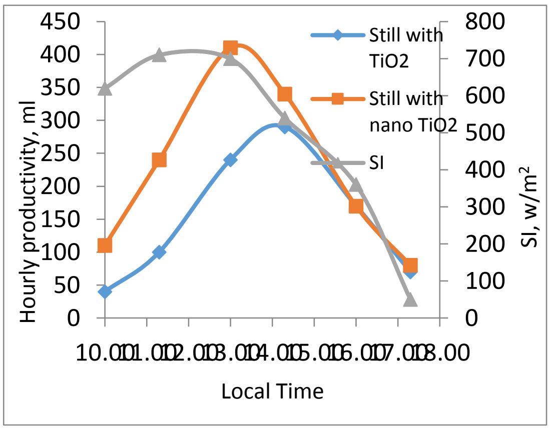

Fig. 6: Change of still hourly productivity with solar intensity

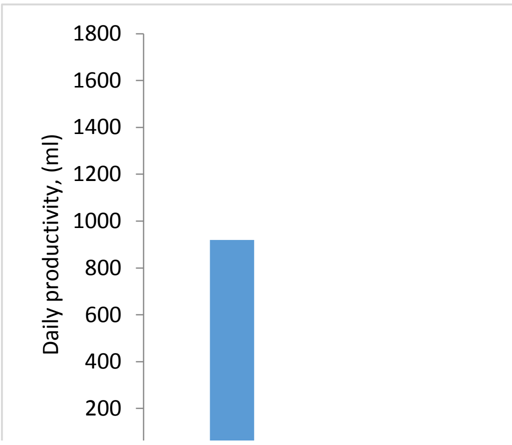

Fig. 7: Effect of using TiO_2 and TiO_2 NPs on daily still productivity

B. 3.2.2. Effect of using different Nano-materials: (TiO2 NPs and ZnO NPs):

The effect of using two different types of nanomaterials on the performance of solar distillers is investigated. The solid nanoparticles studied are titanium dioxide and zinc oxide. The performance was studied for different concentrations of nanoparticles in the pool water (0.15, 0.6, 1.0 and 1.2 g/l).

Fig. 8 shows the cumulative productivity of stills with TiO2 particles, TiO2 NPs or ZnO NPs. It is clear that ZnO NPs have a better effect on the productivity of stills than TiO2 NPs and both are better than TiO2 particles. With increasing catalyst concentration, distillation productivity increased up to a concentration of 0.6 g/l; thereafter, distillation productivity decreased again. This could be due to the fact that increasing the catalyst concentration beyond a certain limit decreases the transparency of water to solar radiation, so that the amount of energy absorbed by the water decreases, which in turn decreases the productivity of the distillation unit [44, 45]. At a catalyst concentration of 0.6 g/l, the productivity of the still with ZnO NPs was 5.4% higher than that of the still with TiO2 NPs. The latter was 39.9% higher than the still with TiO2 particles.

Although the highest productivity is obtained at a catalyst concentration of 0.6 g/l, the difference between the performances of the two materials (TiO2 NPs and Zn NPs) becomes more evident as the catalyst dose increases (productivity of still with ZnO NPs is 22.7% higher than that with TiO2 NPs at a catalyst dose of 1.2 g/l). This could be due to the fact that the heat capacity of the water in the distillation pool increases with increasing catalyst concentration [46], and ZnO NPs have a higher value due to its metallic nature [47]. Experiments with a catalyst concentration of 0.6 g/l (using TiO2 particles, TiO2 nanoparticles, and ZnO nanoparticles) showed that the value of distillation productivity is consistent with solar intensity. Thus, the maximum hourly productivity is reached at noontime, as shown in Fig. 8. These values for hourly productivity give a total productivity of 1645 ml, 1560 ml and 1115 ml for the stills with nano-ZnO, nano-TiO2 and TiO2 particles, respectively. The efficiency of the stills with TiO2 particles, nano-TiO2 and nano-ZnO is 34.93%, 48.87% and 51.53%, respectively.

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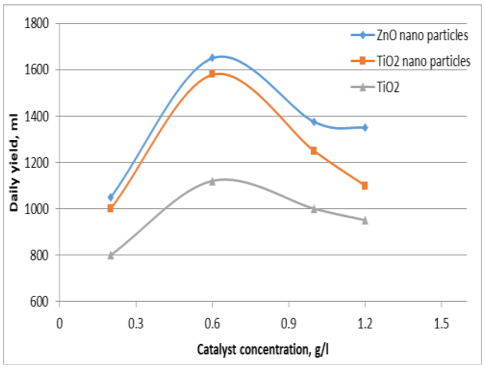

Fig. 8: Effect of using different types of nanoparticles (at solar noon)

4. Conclusion

From the present study, the following conclusion could be drawn:

- The addition of TiO2 to the distillation pool increases the distillation productivity by 43.1% compared to the reference distillation unit . This corresponds to 11% increase in distillation efficiency.
- The effect of TiO2 particles addition becomes more pronounced at midday and around sunshine.
- The magnitude of the temperature gradient (Tb-Tg) is proportional to the magnitude of the distillation productivity. The maximum hourly distillation power is attained at noon (at maximum value of SI).
- The addition of TiO2 NPs further increases the distillation productivity. A maximum increase of 30.1% is achieved at 13:00 by the addition of TiO2 NPs.
- The positive effect of the addition of TiO2 in the form of nanoparticles is more pronounced in the morning period and reaches its maximum value around noon time
- The productivity of the stills is increased by 70.7% by using TiO2 NPs. (compared to the still with TiO2 particles.
- ZnO NPs have a better effect on increasing distillation productivity than TiO2 NPs and both are better than TiO2 particles.
- As the catalyst concentration increases, the distillation productivity increases up to a concentration of 0.6 g/l; then the distillation productivity decreases again.
- The difference between the performances of the two nano materials (TiO2 NPs and ZnO NPs) becomes more evident when the catalyst dose is increased (ZnO NPs is 22.7% higher than TiO2 NPs at a catalyst dose of 1.2 g/l).
- When TiO2 particles, TiO2 NPs and ZnO NPs were used, the efficiencies of stills were 34.93%, 48.87% and 51.53%, respectively.

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