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Improving the thermo-economic performance of hemispherical solar distiller using copper oxide nanofluids and phase change materials: Experimental and theoretical investigation

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Abstract

In the present work, a thermo-economic performance of the modified hemispherical solar still (MHSS) was studied and compared to traditional hemispherical solar still (THSS). The modulations accounted for two additives, namely: paraffin wax as phase change materials (PCM), and copper oxide (CuO) nanoparticles. Three cases of MHSS were investigated and compared to THSS: (0.3 wt%) CuO nanomaterials were immersed in the basin water, implementing PCM container below the basin, and combining PCM container below the basin plus mixing CuO nanoparticles in the basin water. The basin water depth in all stills was set at 1.0 cm in all cases. Moreover, the thermo-economic performance of the four studied cases was compared and evaluated by determining the freshwater productivity, the daily energy efficiency, and the freshwater cost. Experiments have been carried out on the proposed hemispherical distillers under hot climatic conditions of El-Oued (33°27′N, 7°11′E), Algeria. The results show that the single utilization of CuO/water nanofluid and pure PCM improved productivity by 60.41% and 29.17%, respectively, compared to THSS. While, the dual usage of PCM and CuO/water nanofluid further enhanced the productivity by up to 80.20%, relative to THSS. Moreover, the daily energy efficiencies of the hemispherical distillers under the different studied cases (THSS, MHSS/PCM, MHSS/CuO-water nanofluid, and MHSS/PCM+CuO-water nanofluid) were found to be 35.52%, 45.45%, 56.46%, and 63.61%), respectively. The economic feasibility of these modifications presented that the dual usage of PCM and CuO/water nanofluid is more effective as it reduces the cost of freshwater production by 75% compared to THSS.

Graphical abstract

In the third distiller (Modified hemispherical solar still with 0.3 wt% CuO/water nanofluid (MHSS-CuO/water NF)), the modified was done by adding (0.3 wt%) copper oxide (CuO) nanomaterials to the basin water, to improve the thermal properties of nanofluid and increase the intensity of the absorbed solar energy. In the fourth distiller (Modified hemispherical solar still with paraffin wax as phase change materials and 0.3 wt% CuO/water nanofluid (MHSS-PCM+CuO/water NF)), it was designed and constructed a circular galvanized steel container 1 mm thick, 340 mm diameter, and edge height 40 mm, coated with the black pained. This container was placed inside the wooden basin of the hemispherical solar still. A gap of 20 mm thickness was maintained between the container and the wooden basin on the bottom side and sidewall. 2.0 kg of paraffin wax as phase change materials was placed in the gap between the container and the wooden basin, to store the solar energy in the periods of higher solar rays and recovery it in the periods of low solar rays and after sunset. Moreover, in this modification copper oxide (CuO) nanomaterials were also added to the basin seawater with a concentration of 0.3 wt%, to improve the thermal properties of saline water and increase the intensity of absorbed solar energy, and improve the rates of heat transfer.

Introduction

The industrial revolution of the twenty-first century and rapid increase in the population have led to an increase in the global demand for freshwater and energy, as the uses of fuels are countless causing a strong depletion of the non-renewable resources available within the world [[1], [2], [3]]. Electricity production and conventional thermal desalination plants depend mainly on fossil fuels and nuclear sources, however, these energy sources are environmentally polluting and high production cost (due to the production of toxic gases and the creation of a "greenhouse" effect) [[4], [5], [6], [7]]. This has led to very serious negative global climate changes and dire consequences for the environment, such as melting ice, rising water levels on the planet, and an increase in average earth temperature [[8], [9], [10], [11]]. The irrational use and exploitation of fossil fuels lead to serious problems for the ecosystem and the biotic balance, and this is what leads to the collapse of the natural system. The most effective solution to confront these serious challenges is to focus on the use of renewable energy sources at the global level, which is regarded as one of the most prominent challenges today and could provide the necessary quantities of sustainable and clean energy on a large scale [[12], [13], [14]]. Several methods have been devised to eliminate the problem of water scarcity, however, they remain complex due to the technical aspects and their high cost [[15], [16], [17], [18]]. Therefore, many previous studies have shown that using solar energy in the desalination field (solar stills) was very effective since it is abundant and can be accessed free of charge and without cost. Several studies have been conducted on the use of direct solar radiation in the solar water desalination field (solar stills) [[18], [19], [20], [21], [22], [23], [24]]. In our study, we will focus on some of the previous works that could enhance the production of solar distillers.

Bellila et al. [25] investigated experimentally the effects of Al2O3-water nanofluid at different concentrations (0.1, 0.2, and 0.3 wt%) in the hemispherical solar basin. The amount of saltwater used was fixed at 1 L in the basin still. The researchers concluded that the accumulative yield of a hemispherical solar distiller with the utilization of Al2O3-water nanofluid of the 0.1, 0.2, and 0.3 wt%, improvement 41.8, 50.9, and 61.3%, respectively, as compared to the reference case. Benoudina et al. [26] investigated the utilization of Al2O3 micro/nano-particles with various concentrations in solar still. They indicated that the distilled yield was increased by 64.2%, 50.3%, and 34.8% at Al2O3 nanoparticles concentrations of 0.30, 0.20, and 0.10 wt %, respectively, compared to the CSS. Al-Harahsheh et al. [27] experimentally studied the PCM usage in a solar still integrated to a solar water heater. The researchers concluded that the doping of PCM improved the solar still performance. Sarhaddi et al. [28] theoretically conducted the impact of PCM on the efficiencies of the cascade-type solar still. They found that the distilled production rates were 4940 and 3840 ml/m2 with and without using PCM, while the energy efficiencies were 76.69, 74.35% with and without using PCM, as well as the exergy efficiencies were 8.59 and 6.53% with and without using PCM. Sahota and Tiwari [29] theoretically conducted the influences of Al2O3 nanoparticles (0.04, 0.08, and 0.12 wt%) on the performance of double slope basin solar still. They reported that the still with (0.12 wt%) Al2O3 nanoparticles gave higher performance compared to other concentrations for Al2O3 nanoparticles (0.04 and 0.08 wt%). Sahota and Tiwari [30] studied the effects of Al2O3, TiO2, and CuO nanoparticles with weight fractions of (0.2, 0.25, and 0.3 wt%) on the performance of the double slope distiller. They found that the solar still with (0.3 wt%) CuO nanoparticles gave higher performance compared to Al2O3 and TiO2 nanoparticles. Sahota et al. [31] theoretically investigated a passive double slope distiller with Al2O3, TiO2, and CuO/water nanofluids. They deduced that the annual productivity, and the energy, enviro-economic, and exergo-economic performances were outperformed by using CuO-water nanofluid compared to Al2O3/water and TiO2/water nanofluids. Kabeel et al. [32,33] studied the effects of the usage of Al2O3 nanoparticles for improved evaporation rates of single slope solar still and the use of an exterior fan operated by solar panels for improved condensation rates of solar still. They found that the yield of still with using Al2O3 nanoparticles and fan was improved by 116% compared to reference still. While, when using an external condenser (fan) only, the distilled water output was increased by about 53.22%. Kabeel et al. [34] examined the influences of Al2O3 and Cu2O nano-waters at different concentrations (from 0.02 to 0.2 wt%) and the use of an external capacitor for improved water outputs of solar stills. They found that the distilled yield of solar still with Cu2O-water and Al2O3-water nanofluids combined with an external capacitor, was improved by 133.64 and 125.0%, respectively, compared to the traditional distiller. While when using Cu2O-water and Al2O3-water nanofluids only, the distilled water output was increased by about 93.87% and 88.97%, respectively. In followed effort, Kabeel et al. [35] investigated numerically the performance of solar still integrated with an external capacitor and Al2O3 and Cu2O-water nanofluids at different concentrations (from 0.02 to 0.3 wt%) under low-pressure conditions. Researchers have found that the daily efficiency of the solar still with propeller operation was 84.16 and 73.85% using Cu2O and Al2O3 nanoparticles, respectively, while the daily efficiency of conventional still was about 33%. Essa et al. [36] presented a comparative experimental study of the stepped still using two types of basin liners (curved and corrugated), cloth wicks, CuO mixed with paraffin wax, and vapor suction. The authors noted the daily yield of the modified still was improved by 170% compared to conventional still. Thalib et al. [37] presented an experimental study of the tubular solar still performance using PCM and nano-enhanced PCM. The authors noted the daily yield was improved when using nano-enhanced PCM (7.9 kg/m2/d) compared to (6.0 kg/m2/d) for only using PCM. Kabeel et al. [38] conducted an analytical study of the influence of copper tubes filled with PCM on tubular still performance. It was noted that the productivity of the system (8.82–9.05 L/m2/day) was greater than the productivity of conventional still (4.1–4.31 L/m2/day), with 110.0–115.1% productivity enhancement. Yousef and Hassan [39] studied the performance of still incorporated with PCM based on exergy and energy methodologies and energy payback time. The results found that adding PCM to the solar distillation system increased the annual energy savings by 10% and increased the exergy by 3.0%. Mousa et al. [40] investigated experimentally the effects of copper tubes filled with PCM (tricosane) in the solar basin of the distiller. The amount of PCM was varied to analyze the ratio between the mass of PCM and the mass of water. The amount of saltwater used was fixed at 3 L in the basin still. The researchers concluded that during the nighttime distilled water was directly proportional to the PCM to water mass ratio.

The previous reviewed findings show that a lot of studies have been conducted on studying the effect of basin coating material, nanomaterials, cover cooling techniques, and thermal storage materials on ameliorating the performance of conventional solar stills. To the best of our knowledge, combining the development of new designs of solar stills with the inclusion of performance enhancers such as thermal storage materials, nanofluids, cooling films, and nano paints have not been simultaneously utilized to increase the productivity of the solar stills. Herein, the present study attempted to analyze the developed design of solar distiller not only by introducing a new design of solar still but also using different additives within the developed solar still.

For this aim, four distillers were designed, fabricated, and tested namely; modified hemispherical solar still with paraffin wax as phase change material (MHSS-PCM), modified hemispherical solar still with 0.3 wt% CuO/water nanofluid (MHSS-CuO/water NF), modified hemispherical solar still with paraffin wax as phase

change material and 0.3 wt% CuO/water nanofluid (MHSS-PCM+CuO/water NF), and traditional hemispherical solar still (THSS) as reference distiller to evaluate and compare their thermo-economic performance in terms of freshwater productivity, daily energy and exergy efficiency, and freshwater cost. The experiments were carried out at the same conditions under hot climatic conditions of El-Oued (33°27′N, 7°11′E), Algeria on four diversified modified cases: MHSS with 0.3 wt% CuO nanoparticles mixing in the basin water, MHSS with pure PCM container below the basin, MHSS combined PCM container below the basin plus mixing CuO nanoparticles in the basin water, and the fourth case was traditional hemispherical solar still (THSS) as reference distiller. The basin water depth in all stills was set at 1.0 cm in all four cases. In addition, a thermo-economic analysis model is also developed to obtain and compare the internal heat and mass transfer coefficients, energy and exergy efficiencies, and freshwater production cost of the different modifications applied to the hemispherical distillers.

Section snippets

Nanofluid preparation and characterization

CuO nano-materials are chosen and utilized in the current study, due to their superior thermal conductivity and low cost. Table 1 shows the specifications of the CuO nanoparticles utilized in the present experimentations. Since CuO nanoparticles are difficult to dissolve in saltwater due to their hydrophobic nature. The next proceedings are applied to prepare soluble and homogenous CuO/water nano-mixture. The CuO nanopowder and water are blended by using a magnetic stirrer for 30 min, and…

Theoretical model

The performance of the four tested hemispherical distillers is assessed based on energy and exergy analyses. This evaluation could assist in not only assessing the freshwater productivity for each distiller but also the mechanisms of heat transfer related to concerned the saline water condensation and vaporization processes. Generally, mechanisms of heat transfer associated with solar still can be divided into two key types: external or internal mechanisms. The internal heat transfer mechanism…

Results and discussion

The experiments are conducted on the proposed hemispherical solar stills (THSS, MHSS with PCM container, MHSS with 0.3 wt% CuO/water NF, and MHSS integrated with PCM container and 0.3 wt. CuO/water NF) for some typical days over a complete 24 h cycle in September 2021 at the same hot climatic conditions of El-Oued (33°27′N, 7°11′E), Algeria, to augment and compare the distilled yield as well as to achieve the effects of utilizing PCM and CuO nanoparticles on the still performance. The key aim…

Comparison of the present study with published similar works

In Table 4, the results of the present study are compared with published similar works. From Table 4, it can be noticed that the distilled yield of a single slope still with Nano-ZnO [42] is minimum with a value equal to 12.67%. However, for the tubular solar still, with PCM, it is maximum with a value equal to 115.1% [45]. The obtained amelioration in total water production exhibited a good performance of the different modifications applied in the present study compared to those revealed by…

Economic evaluation

Based on the economic analysis described before. Table 5 shows a detail of the total costs of the four cases covered by the current study (THSS, MHSS with PCM, MHSS with CuO/water NF, and MHSS with PCM+CuO/water NF). As shown in Table 5, the total distillate cost per liter was 0.01144, 0.00905, 0.00719, and 0.00645 for THSS, MHSS with PCM, MHSS with CuO/water NF, and MHSS with PCM+CuO/water NF, respectively. The economic feasibility results indicated that the use of paraffin wax as phase…

Conclusions

This work presented a comprehensive experimental study of modified hemispherical solar still (MHSS) compared to traditional hemispherical solar still (THSS). Two additives were prepared and used as system performance improvers: paraffin as phase change material (PCM) and CuO/water nanofluid (NF). Three cases of MHSS were examined and compared to THSS under hot climatic conditions of El-Oued (33°27′N, 7°11′E), Algeria: in first case 0.3 wt% CuO nanoparticles were immersed in the basin water…

CRediT authorship contribution statement

Mohamed Abdelgaied: Writing – original draft, Methodology, Formal analysis. **Mohammed El Hadi Attia:** Conceptualization, Data curation, Investigation. **A.E. Kabeel:** Validation, Supervision, Conceptualization. **Mohamed E. Zayed:** Methodology, Writing – original draft, Writing – review & editing.…

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.…

References (45)

M. Elashmawy *et al.*
Enhancing tubular solar still productivity using composite aluminum/copper/sand sensible energy storage tubes
Sol. Energy Mater. Sol. Cells (2021)

M.E. Zayed *et al.*
A comprehensive review on Dish/Stirling concentrated solar power systems: design, optical and geometrical analyses, thermal performance assessment, and applications
J. Clean. Prod. (2021)

M.M.Z. Ahmed *et al.*
Enhancing tubular solar still performance using double effect with direct sunrays concentration
Sol. Energy Mater. Sol. Cells (2021)

A.E. Kabeel *et al.*
Improvement of thermal performance of the finned plate solar air heater by using latent heat thermal storage
Appl. Therm. Eng. (2017)

M.E. Zayed *et al.*

Chapter 12 - high-temperature solar selective absorbing coatings for concentrated solar power systems

A.F. Mohamed *et al.*
Enhancement of a solar still performance by inclusion the basalt stones as a porous sensible absorber: experimental study and thermo-economic analysis
Sol. Energy Mater. Sol. Cell. (2019)

A.E. Kabeel *et al.*
Performance enhancement of modified solar still using multi-groups of two coaxial pipes in basin
Appl. Therm. Eng. (2017)

A.E. Kabeel *et al.*
Effect of graphite mass concentrations in a mixture of graphite nanoparticles and paraffin wax as hybrid storage materials on performances of solar still
Renew. Energy (2019)

M.E. Zayed *et al.*
Applications of cascaded phase change materials in solar water collector storage tanks: a review
Sol. Energy Mater. Sol. Cell. (2019)

M.E.H. Attia *et al.*
Enhancement of hemispherical solar still productivity using iron, zinc and copper trays
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