Performance enhancement of modified double slope passive solar still using different water-based nanofluids

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Abstract. The aim this study is to analyze the performance of a modified double slope passive solar still (MDSPSS) with and without using water-based nanofluids along with harvesting solar energy. For this, three types of water-based nanofluids used as Aluminum Oxide (Al₂O₃), Zinc Oxide (ZnO) and Copper Oxide (CuO) at different concentrations. This might be an alternative energy source for the existing conventional type of desalination. Consequently, analyzed physical and finalized the suitable water nanofluid for further experimental work. This paper describes a unit which is designed on simple principles of evaporation and condensation with no electricity being used. Thus we harness the heat radiated by the sun to accomplish the evaporation process. After that the condensation process will be start with natural temperature difference between heated and non-heated segment. This modified system with nano-fluid-based as a heat source has made to observed that the effect of different operating modes at climate conditions (month of March 2019) of Lucknow city, India. After experimental result comparison, found that the Aluminum Oxide (Al₂O₃) nanofluid has 36.55% higher productivity and through Copper oxide (CuO) and Zinc Oxide (ZnO), water nanofluid has 15.26% and 21.75% higher production rate respectively concerning still water. The payback period is also calculated for this modified system with nanofluids as 121 days, which is less than that of the unit with normal water.

Keywords: Solar desalination, Nanofluids, Solar energy, Potable water, Productivity.

1. Introduction
Today, water scarcity (or water crises) has become a worldwide issue and almost every country faces the problem of water crises. Water resources around the world have been continuously exploited and polluted. Energy crises, unsustainable cultivation, human anthropogenic activities, changes of dynamics of climate change; clouds formation, and hydrological cycle (or linkages among these) are the main cause of widespread water scarcity [1,2]. Because of the current circumstances, solar energy-based solar desalination system drags everyone’s attention to address the global water shortage problems and providing a clean and sustainable option to the users without a carbon footprint on the environment [3,4]. Solar distillation unit is a very simple and ecumenical for the production of potable/drinking water by solar energy. The basic working principle of this technique is evaporation process from basin surface to water and condensation process from water vapor to covered glass surface (lower part), so its production rate depends on both phenomena. It can be very useful especially in desert areas or where electricity not available. This technique is comparatively shameful to construct, maintenance is very less and reduces the shortage of drinking water supply. Due to its production rate, it using very limited, so it is the drawback of this process. [5, 6].

In the time-span of the last four-five decades, keeping all these aspects of solar stills, scientists and researchers working on various experimental and numerical techniques to augment the working temperatures and thus productivity rates. Therefore, different techniques and augmentation methods are employed on solar stills to enhance its productivity through deployment of inside/outside auxiliary systems to increase the heat (or temperature) input inside the solar stills such as PV/T collector [7,8], phase change materials (PCMs) [9,10], external reflector [11], PCMs with solar collector [12], additional condenser [13], and application of nanofluids [14,15,16,17]. Sahota and Tiwari [18] carried
out exergoeconomic and enviroeconomic analysis for the integrated solar still (double slope) system with and without helically coiled as heat exchanger using aluminum oxide (Al$_2$O$_3$), titanium oxide (TiO$_2$) and copper oxide (CuO) water-based nanofluids. Authors are observed that the exergoeconomic parameter as 0.151 kWh/Rs. (system without heat exchanger) and 0.103 kWh/Rs. (system with heat exchanger) laden with water (base fluid), respectively, at $i = 4\%$ and $n = 50$ years of the systems. Hassan et al. [19] revealed that the exergoeconomic and exergoenvironmental parameters for conventional solar distiller (accommodate sand in the basin) integrated with parabolic type collector (trough) are found to be 6.17 kWh/$ (at 12\% interest rate and 10 years lifetime of the system) and 5.9 ton CO$_2$/year, respectively, among different studied solar systems with their specifications. Sharshir et al. [20, 21] examined (experimentally) the exergoeconomic and exergoenviroeconomic explication of modified solar distiller loaded with Fe$_3$O$_4$ and CuO nanoparticles and with cotton hung pad in place of wick. Authors examined that the exergoeconomic, exergoenvironmental, and exergoenviroeconomic parameters are found as 6.939 W/$, 3.028$ ton CO$_2$/year, and 43.906$/year, respectively, for modified solar still laden with CuO nanoparticle.

The unique aspect of this study is the utilization of different nanofluids to increase heat the water initially from the basin such that the water being heated by the sheet evaporates at an increased rate due to incoming water having an elevated temperature. The project depends upon the amount of sunlight that hits the black bottom surface. Considering this dependency the setup is set to pivot about in its given radial area, to obtain maximum sunlight throughout the day.

Therefore, in this research, a detailed and complete conducted/performed on the modified double slope passive solar still (MDSPSS) with adding different metal oxides to enhance the yield and performance of the system. This study is carried out based on experimental data observed for the climatic condition of Lucknow (Latitude/Longitude: $26^\circ84^\prime$ N/$80^\circ94^\prime$ E), Uttar Pradesh, India along with comparative analysis (with and without nanofluids). Furthermore, performance analysis and other aspects such as the cost of produced water (distilled) per litre along with the payback time is calculated and discussed in detail for the aforesaid systems.

2. Material and Methods

2.1. Fabrication and working of modified solar still

In this present work, the experimental setup of the modified solar still (single basin-type) is fabricated to detect the effect of incorporating modifications on the performance indicator such as enhanced productivity. The material used for the fabrication was Fiber Reinforced Plastic (fiber-reinforced polymer (NEMA Grade G-10/EP3) reinforced with glass fibers) and Acrylic (polymethyl methacrylate-PMMA). The principle behind using two material for construction is stem from the concept of ‘Equivalent Thickness’ for the equal rate of heat transfer/loss from the solar still system. The basin and north wall of solar still painted with black color act as an insulation layer between ambient and solar still unit to retard the heat losses up to the limit. The three side walls (east, west, and south) of the solar still are made by 3 mm thick of transparent acrylic sheet and north wall by FRP sheet. The basin has taken an area with 2 m$^2$ in fabricated double slope (MDSPSS). The basin surface and north wall are painted with black dye to absorbed the highest amount of sun rays. FRP sheet also acts as an insulation layer between ambient and solar still unit to retard the heat losses up to the limit. The three side walls (east, west, and south) of the solar still are made by 3 mm thick of transparent acrylic sheet and north wall by FRP sheet. Two glass covers with dimensions 1.03 x 1.03 x 0.004 m$^3$ are used and fixed in the frame along an inclination angle of 15$^\circ$ with respect to the horizontal surface. Window putty and silicon rubber gasket were used as a sealant fixing to reduces vapor leakage, air-void between the outside environment and edges of the system to reduce the upper and side heat losses from the modified solar still [22,23]. Condensed or distilled yield (water) trickles down toward small channels (troughs) attached at the inner side of walls and come out to the outlet point of each trough, and then received by measuring jar through PVC pipes. Two insertion holes are also given at the north
wall (rear side) of the solar unit, one inlet for thermocouple wires and another for pouring contaminated water into the solar still by a pipe. This experimental setup is fixed on an iron supported stand at the terrace of Chemical Engineering Department, IET Lucknow (Latitude/Longitude: 26°84’ N/80°94’ E), U.P., India.

![Figure 1. Pictorial view of experimental setup.](image)

Figure 2 shows the points where thermocouples are placed in MDSPSS to measure thermal radiation on hourly basis at various locations like inside and outside walls & glass temperatures, water and basin temperatures of the still.

![Figure 2. Schematic diagram of MDSPSS and location of thermocouples.](image)

2.2. Equivalent Thickness Calculation

The concept of equivalent thickness is used to analyze the rate of heat transfer or reduction for fabrication of solar still’s wall (except north wall) with 5 mm of FRP. The vital effective thickness can be calculated by using Fourier's law (Eqs. 1,2) with surface temperatures between $T_1$ and $T_0$ [4].
\[ Q = \frac{K_{FRP}.A_{FRP}(T_1 - T_0)}{L_{FRP}} = \frac{K_{ACRY}.A_{ACRY}(T_1 - T_0)}{L_{ACRY}} \]  \hspace{2cm} (1)

\[ L_{FRP} = \frac{L_{FRP}.K_{FRP}}{K_{FRP}} = \frac{0.2 \times 5}{0.351} = 3 \text{ mm} \]  \hspace{2cm} (2)

K_{FRP} = 0.351 \text{ W/m.K}, \; K_{ACRY} = 0.2 \text{ W/m.K}, \; Q = \text{heat transfer rate by used FRP material and } T_1 \; \& \; T_0 = \text{both side wall temperature. That's why 3.0 mm thickness of acrylic sheet (transparent) used in place 5.0 mm of FRP sheet for fabrication of South, East and West walls. Due to deviation of ambient temperature and solar radiation, the MDSPSS system is not considered as steady-state condition because wind velocity is assumed in steady-state. Therefore, for calculating equivalent thickness, considered the different inner side temperature of still such as (i) inner glass cover, (ii) filled water, (iii) basin surface, (iv) formed vapor, and (v) inner wall temperatures which are constant throughout for every hourly basis calculation.}

### 2.3. Procedure for nanofluids preparation

In this study, different water-based nanofluids such as Aluminum Oxide (Al₂O₃), Copper Oxide (CuO) and Zinc Oxide (ZnO) have been taken depends on their thermal conductivity as well as economically suitable [24]. Proper preparation of nanofluid is an important factor for enhancing the thermal conductivity because these are behaved like hydrophobicity, prone to agglomerate jointly and very fast settle down. The sodium dodecylbenzene sulphonate (SDBS) is used as a surfactant for maintaining the stability along with suspension form [25]. After mixing, prepared a sample was stirred with a magnetic stirrer for up to 30 min and after that put on ultrasonicator for 2 hours. For good stability and thermal conductivity, the weight concentration should be less than 0.5\% [14]. In this work, firstly, 50 ml of prepared water-based nanofluid samples were made with three concentrations as 0.2 \%, 0.25\%, and 0.3\% and checked for those stability to find out the 0.25 \% is a good concentration which has more stability to others and it tested with MDSSS. Figure 3 shows that the procedure for the preparation of nanofluid with flowing 2-way methods.

\[ \text{Amount of nanoparticles (gm)} = \frac{\text{Concentration (\%)} \times \text{Vol. of water (ml)} \times \text{Density of nanoparticles (gm/ml)}}{100} \]  \hspace{2cm} (3)

**Figure 3.** Stepwise procedure for the preparation of nanofluids.
Table 1. Thermal conductivity with different concentration.

| S. No. | Nanofluids                | Concentration | Thermal conductivity (W/m²K) | Increment (%) |
|--------|---------------------------|---------------|------------------------------|---------------|
| 1      | Aluminum Oxide (Al₂O₃)   | 0.25%         | 0.6435                       | 11.35         |
| 2      | Zinc Oxide (ZnO)         | 0.25%         | 0.6410                       | 8.150         |
| 3      | Copper Oxide (CuO)       | 0.25%         | 0.6318                       | 6.15          |

2.4. Experimental procedure

Before carried out experimentation on the modified solar still, the basin of setup is properly cleaned and removed organic/inorganic pathogens, salts, etc. from the system. The experimental setup was orientated in an East-West direction to obtain the highest solar intensity. Then, contaminated (feed) water is poured into the basin and filled upto depth of 1.0 cm. The basin is filled with the required quantity of water at the desired water depth, one day before the start of the experiment to bring the system in a steady-state condition before starting the experimental measurements. On the day of experimental work, an hour before starting the experiments, the quantity and level of water depth was checked carefully along with proper inspection of any leakage, insulation between system parts, etc. The condensing glass covers were cleaned properly before the commencement of the experiments. Nanofluids also enter by inlet pipe and through drainage, a valve to collect spent nanofluids for further use. Experiments at 1.0 cm water depth were started at 07:00 a.m. (local time of Lucknow) in the morning and continued for 12 hours until 07:00 p.m. Experimental data (average value of experimental observations) for any typical day were taken at each one-hour time interval (hourly basis) and recorded for 12 hours (from 07:00 am to 07:00 pm). The experiments were performed in the month of March, 2019. During experimentation, various measuring instruments with their operating ranges are used with those accuracies and error limits which were mentioned in Table 2. In this study, Type –T Copper Constantan calibrated thermocouples are used. These thermocouples have been calibrated with the help of glass thermometer.

Table 2. Accuracy and error limits of measuring instruments.

| S. No. | Instruments          | Accuracy | Range       | % error |
|--------|----------------------|----------|-------------|---------|
| 1      | Thermocouple         | +0.1 °C  | 0-150 °C    | 0.5%    |
| 2      | Digital temperature indicator | +0.1 °C | 0-450°C    | 0.25%   |
| 3      | Thermometer          | +1 °C    | 0-100 °C    | 0.25%   |
| 4      | Solarimeter          | +1 W/m²  | 0-25000 W/m² | 2.5%   |
| 5      | Measuring Jar        | +10ml    | 0-1000 ml   | 10%     |

3. Results and Discussion

Table 1 represented that the thermal conductivity of used nanofluids with 0.25% concentration along with base water and their % increases. It has been observed that Aluminum Oxide (Al₂O₃) gives the maximum thermal conductivity as compared with Zinc Oxide (ZnO), Copper Oxide (CuO), and water. Figure 4 depicts that the effect of basin fluid temperature with solar time at 0.25% concentration of different nanofluids and maximum temperature was found as 78.2°C through Al₂O₃ at 15:00 hr, similarly through ZnO and CuO were found as 71.5°C & 66.7°C at 16:00 hr, respectively. Similarly, figure 5 depicts that the effect of productivity with solar time at 0.25% concentration of different nanofluids along with base water and maximum productivity was found as 1780 ml through Al₂O₃ at 15:00 hr, similarly through ZnO and CuO were found as 1650 ml & 1510 ml at 15:00 hr, respectively. It is seen that the temperature variation and production rate depend on the change of thermal
conductivity and convective heat transfer coefficient of nanofluids. It means, the rate of potable water production is a function of their thermal conductivity.

Due to increasing the rate of heat transfer, the evaporation rate was found higher which improved performance of the solar unit. Figure 6 depicts the cumulative productivity of different nanofluids at 0.25 concentrations along with base normal water. It was observed that the maximum productivity was found as 11209 ml/day through Aluminum Oxide (Al₂O₃) and as 9994 ml/day & 9461 ml/day through ZnO and CuO, respectively. It means productivity through all three nanofluids is better as compared with base water. The effect of production by nanofluids is far better than the conventional still with
water (basin water). The production rate is about 36.55% greater by Al$_2$O$_3$ as compared to conventional solar still. Figure 7 depicts that, the comparative increment (% basis) of used nanofluids along with base water as taken basin water. The modified still gave better productivity as with Aluminum Oxide (Al$_2$O$_3$) 36.55% more followed by 21.75% for ZnO and 15.26% for CuO. This study confirms that the vital role of thermal conductivity and it is a good indication for enhancing the yield of the system. Also analyzed various physicochemical parameters of water (before and after distillation) by using a water testing kit and found good agreement as per WHO standards.

![Graph 1](image1)

**Figure 6.** Cumulative productivity with different fluids.

![Graph 2](image2)

**Figure 7.** Increase (%) of production rate with nanofluid.
4. Thermal efficiency (daily efficiency) of MDSPSS

The overall thermal efficiency of the solar unit is represented by the ratio of total heat transfer rate (total distillate output) to the total heat input into the solar by incident solar thermal radiation and it is expressed as following equations [26, 5]:

\[ \eta_0 = \frac{\sum \dot{m}_{ew} \times L_{vap}}{\sum (I(t) \times A_{ss} \times 3600)} \]  

Similarly, the overall thermal efficiency of MDSSS:

\[ \eta_0 = \frac{\sum_{i=1}^{12} \dot{m}_{ew} \times L_{vap}}{\sum_{i=1}^{12} I(t)_{\text{input}} \times dt} \times 100 \]  

During the off sunshine hour, the value of \( I(t) \) and \( I(t)_{\text{input}} \) taken zero. Where, \( \eta_0 \) is the overall thermal efficiency, \( \dot{m}_{ew} \) is the mass of evaporated water (ml/hr), \( L_{vap} \) is the latent heat vaporization (kJ/kg), \( I(t) \) and \( I(t)_{\text{input}} \) are the solar intensity (W/m\(^2\)) can be evaluated using expressions reported as:

\[ L_{vap} = 3.1615 \times 10^6 [1 - (7.616 \times 10^{-4} \times T_v)] \text{ for } T_v > 70^\circ C \]  
\[ L_{vap} = 2.4935 \times 10^6 \left[ 1 - (9.4779 \times 10^{-4} \times T_v) + (1.3132 \times 10^{-7} \times T_v^2) - (4.7974 \times 10^{-9} \times T_v^3) \right] \text{ for } T_v < 70^\circ C \]  

The total input energy i.e. solar energy (instantaneous) to the solar unit by glass cover(s) and transparent walls is expressed by the following equation:

\[ I(t)_{\text{input}} = I_{Eg}(t) \times A_{Eg} + I_{Wg}(t) \times A_{Wg} + I_E(t) \times A_E + I_W(t) \times A_W + I_s(t) \times A_s \]  

Where, \( A_{Eg} \) & \( A_{Wg} \) = East and Westside glass cover area (m\(^2\)), \( A_E \) = Glass cover area (m\(^2\)), \( A_W = \) South and West sidewall area (m\(^2\)), \( \dot{m}_{ew} = \) Total mass of distillate collected in a jar (kg/hr), \( A_{ss} = \) Area of solar still in (m\(^2\)).

5. Economical Analysis

To check the viability of any process, the cost analysis is an important component. For this work, the evaluation of the payback period has been done considering the operating cost, maintenance cost, and capital cost of the entire system. The total manufacturing cost of modified solar still is considered in terms of capital cost (\( P_{\text{cost}} \)). The salvage value (15%), annual maintenance cost (15%), and rate of interest (12%) are considered for calculation. The daily (average value) production of the MDSPSS is found as 5.6 lit/m\(^2\). From the economical point of view of MDSPSS, 320 days are considered as clear days, and the left over 45 days are considered as hazy/rainy days for the climatic condition of Lucknow (Uttar Pradesh), India. The procedure for calculation of payback time/period is mentioned by following equations:

Daily distilled water production per day = 11.2 lit/day (during the day time in summer season)
Indian market cost of distilled water (IMCDW) = Rs. 15/lit
The cost of the entire system has been increased by 25% by using nanofluids. Table 3 shows that the total cost analysis of the system. Although the total cost of the system is more, its productivity has
been increased up to 36.55%, which gave good reason for the high asset. The payback period is calculated for this MDS-PSS system with nanofluids as 121 days, which is less than that of the still with ordinary water.

**Table 3. Economical analysis based on one-day production data through MDSSS.**

| Materials and components                  | The total cost of the item (Rs.) | Cost type   | Value (Rs.) |
|------------------------------------------|----------------------------------|-------------|-------------|
| FRP sheet (5mm thick)                    | 4750/-                           | CRF         | 0.147       |
| Acrylic sheet (3 mm thick)               | 2440/-                           | SFF         | 0.027       |
| Iron stand and pipes                     | 580/-                            | Principle cost ($P_{cost}$) | 17600/-     |
| Inlet/Outlet nozzle                      | 80/-                             | Salvage value ($S_V$)          | 2112/-      |
| Black paint                              | 120/-                            | Life of solar still ($n$)      | 15 years    |
| Plastic clips                            | 75/-                             | Annual first cost ($A_{FC}$)   | 2587.2/-   |
| Aero tape                                | 85/-                             | Annual salvage value ($A_{SV}$) | 475.21/-   |
| Silicon rubber (gasket)                  | 360/-                            | Annual maintenance cost ($A_{MC}$) | 388.08/- |
| Glass putty                              | 110/-                            | Total annual cost ($T_A$)       | 5000/-      |
| Top glass cover (4mm thick)              | 1100/-                           | Annual yield ($A_Y$)            | 3264.0 lit  |
| Nanofluids (Al$_2$O$_3$, ZnO, CuO)       | 4400/-                           | Annual useful energy ($A_{UE}$) | 2046.5 kWh |
| Fabrication cost                         | 3500/-                           | Annual cost of potable water per lit ($A_{CPW}$) | 0.79 Rs/lit |
| **Total cost (Rs.)**                     | **17,600/-**                     | Annual cost of potable water per kWh | 2.44 Rs/kWh |
|                                          |                                  | Net profit ($N_P$)              | 46381.4/-   |
|                                          |                                  | Payback period ($P_P$)           | 121.4 days  |

* Costs are based on Lucknow (U.P), India market rate.

6. Conclusion

This study shows that the performance analysis of MDSPSS with base water, Aluminum Oxide (Al$_2$O$_3$ Copper Oxide (CuO)), and Zinc Oxide (ZnO) water-based nanofluids. It was observed that the potable water production rate was 36.55% more through Aluminum Oxide nanofluid for Zinc Oxide and Copper Oxide nanofluids than the solar still with base water i.e. (Al$_2$O$_3$>ZnO>CuO>water). It clearly says that the higher thermal conductive nanofluid absorbs higher sun rays than the base water. The production rate still increases due to the creation of maximum temperature difference between basin fluid and upper glass cover. It also observed that the thermal conductivity of nanofluids and weather conditions play a vital role in improving the yield of solar still. Also calculated average daily productivity is 5.6 lit/m$^2$, the annual produced water cost is 0.79 Rs./lit, and the payback period with nanofluid is 121 days.

7. References

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