Performance analysis of \( N \) identical PVT-CPC collectors with an active single slope solar distiller and helically coiled heat exchanger using CuO nanoparticles

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ABSTRACT

This paper presents performance analyses based on temperatures, thermal energy (overall), thermal exergy (overall), electrical exergy, and yield of the systems that have been investigated. In the present study, an analytical expression of \( N \) identical partly covered photovoltaic compound parabolic concentrator collectors connected in series (\( N \)-PVT-CPC-SS-HE) with an active single slope solar distiller unit and helically coiled heat exchanger has been found. The performance analyses of the proposed system have been executed for 0.25% concentration of CuO nanoparticles for collectors (\( N = 4 \)), and fluid-flow rate 0.02 kg/s in 280 kg mass of basin fluid. The system’s performance is compared with a previous system of \( N \) identical partly covered photovoltaic flat plate collectors connected in series (\( N \)-PVT-FPC-DS-HE) with an active double slope solar distiller unit and helically coiled heat exchanger. The thermal energy is 112,109.1 kWh, thermal exergy 312.07 kWh, and yield 3,615.05 kg annually. It is found that daily enhancement in thermal energy of the proposed system with CuO nanoparticles compared with the previous system with various nanofluids CuO, Al\(_2\)O\(_3\), TiO\(_2\), and water is found to be 16.75%, 51.13%, 61.82%, and 80.67% more significant correspondingly. The enhancement in yield of the proposed system is obtained for CuO nanoparticles greater than the previous system with CuO by 11.19%, Al\(_2\)O\(_3\) 17.2%, TiO\(_2\) 26.25%, and water 32.17%. The electrical exergy is almost the same as the previous system.

Key words: active solar distiller unit (\( N \)-PVT-CPC-SS-HE), CuO nanoparticles, helically coiled heat exchanger, overall thermal energy

HIGHLIGHTS

- Analyzed single slope \( N \)-PVT-CPC-HE system.
- Overall thermal energy has been computed.
- Overall thermal exergy has been calculated.
- Annual yield for proposed system has been evaluated.
- CuO nanoparticles.

NOMENCLATURE

\( A_{BA} \)  
basin surface, in (m\(^2\))

\( A_{CA} \)  
flat plate collector area under glazing, in (m\(^2\))

\( A_g \)  
glass cover area, in (m\(^2\))

\( A_m \)  
PVT area, in (m\(^2\))

\( C_p \)  
Specific heat NPs, in (J/(kgK))

\( C_{bf} \)  
basematerial specific heat, in (J/(kgK))

\( C_{nf} \)  
specific heat nanofluid, in (J/(kgK))

\( D_t \)  
FPC tube dia., in (m)

\( D_p \)  
NPs dia., in (nm)

\( F' \)  
dr factor of collector efficiency

\( h_i \)  
coefficient of heat transfer glazing to absorbing plate, in (W/(m\(^2\)K))

\( h_o \)  
heat transfer coefficient, top of PVT to ambient air, in (W/(m\(^2\)K))

\( h_{pw} \)  
heat transfer coefficient, blackened plate to fluid, in (W/(m\(^2\)K))

\( h_{bw} \)  
heat transfer coefficient, basin liner to ambient air, in (W/(m\(^2\)K))

\( h_{ba} \)  
coefficient of heat transfer from sink liner to ambient air, in (W/(m\(^2\)K))

\( h_{CPC} \)  
coefficient of heat transfer convective in CPC, in (W/(m\(^2\)K))

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$h_{HE}$ coefficient of heat transfer convective in heat exchanger, in $(W/(m^2K))$
$h_{weg}$ coefficient of heat transfer radiative, water to glass cover, in $(W/(m^2))$
$h_{cwg}$ coefficient of heat transfer convective, water to glass cover, in $(W/(m^2))$
$h_{ewg}$ coefficient of heat transfer evaporative, water to glass cover, in $(W/(m^2))$
$h_{1g}$ total heat transfer coefficient, in $(W/(m^2))$
$h_{1w}$ total heat transfer coefficient, water to glass cover, in $(W/(m^2))$
$I_b$ solar intensity over collector, in $(W/m^2)$
$I_g$ solar intensity over glass cover, in $(W/m^2)$
$K_g$ thermal conductivity of glass, in $(W/(mK))$
$K_p$ thermal conductivity of absorbing plate, in $(W/(mK))$
$K_p$ thermal conductivity of nanoparticle, in $(W/(mK))$
$K_{bf}$ thermal conductivity of basefluid, in $(W/(mK))$
$L$ helical coiled heat exchanger length, in (m)
$L_c$ collector length under glazing, in (m)
$L_i$ insulation thickness, in (m)
$L_g$ glass cover thickness, in (m)
$L_m$ PVT length, in (m)
$L_p$ absorption plate thickness, in (m)
$M_w$ basin water mass, in (kg)
$M_{ew}$ yield, in (kg)
$m_{l1}$ mass flow rate of water, in (kg/s)
$PF_1$ by the glass cover module, penalty factor
$PF_2$ by the absorption plate under module, penalty factor
$PF_3$ by absorbing plate to glazed portion, penalty factor
$PF_c$ by glass cover for glazed portion, penalty factor
$P_{gl}$ partially saturated vapor pressure of glass cover, in (N/m$^2$)
$Q_{an}$ heat transfer rate to $N$ identical 25% PVT-CPC connected in series, in (kWh)
$r_{11}$ outer dia. of helical coiled heat exchanger tube, in (m)
$r_{22}$ inner dia. of helical coiled heat exchanger tube, in (m)
$T_{gl}$ inside-glass cover temperature, in (°C)
$T_{go}$ outside-glass cover temperature, in (°C)
$T_a$ ambient temperature, in (°C)
$T_c$ solar cell temperature, in (°C)
$T_{CN}$ average solar cell temperature, in (°C)
$T_{ib}$ temperature of fluid at inlet, in (°C)
$T_{bf}$ basefluid temperature of collector, in (°C)
$T_{woN}$ at the end of N-PVT-CPC, water outlet temperature, in (°C)
$T_{nf}$ temperature of nanoparticle, in (°C)
$T_p$ temperature of absorption plate, in (°C)
$T_s$ temperature of sun, in (°C)
$T_v$ vapor temperature in (°C)
$T_w$ basin water temperature, in (°C)
$T_{wo}$ water temperature at $t = 0$, in (°C)
$\Delta T_{DSSS}$ temperature difference between nanoparticle and basefluid at DSSS, in (°C)
$\Delta T_{CPC}$ temperature difference between nanoparticle and basefluid at PVT collector outlet, in (°C)
$\Delta T_{HE}$ temperature difference between nanoparticle and basefluid at heat exchanger, in (°C)
$\Delta T$ temperature difference between $T_w$ and $T_{gl}/T_{glw}$ for time (t), in (°C)
$U_{ba}$ coefficient of overall heat transfer, sink lining to ambient, in $(W/(m^2K))$
$U_{ga}$ coefficient of overall heat transfer, condensing cover to ambient air, in $(W/(m^2K))$
$U_{La}$ coefficient of overall heat transfer, glazing to ambient air, in $(W/(m^2K))$
$U_{Lm}$ coefficient of overall heat transfer, module to ambient air, in $(W/(m^2K))$
$U_{ca}$ coefficient of overall heat transfer, solar cell to ambient air, in $(W/(m^2K))$
$U_{cp}$ coefficient of overall heat transfer, absorbing plate to ambient air, in $(W/(m^2K))$
$X$ characteristic length, solar distiller unit, in (m)

GREEK LETTERS

$\alpha_g$ condensing-cover-absorbed fraction of solar energy
$\alpha_b$ basin-surface-absorbed fraction of solar energy
\( \alpha_f \) flui-absorbed fraction of solar energy
\( \alpha_c \) solar-cell-absorbed fraction of solar energy
\( \beta \) packing factor
\( \beta_p \) nanoparticle thermal expansion coefficient, in \((K^{-1})\)
\( \beta_{nf} \) nanofluid thermal expansion coefficient, in \((K^{-1})\)
\( \beta_{bf} \) basefluid thermal expansion coefficient, in \((K^{-1})\)
\( \phi_v \) volume fraction of nanoparticles, in (%)
\( \mu_{bf} \) basefluid dynamic viscosity, in \((Ns/m^2)\)
\( \mu_{nf} \) nanofluid dynamic viscosity, in \((Ns/m^2)\)
\( \eta_e \) efficiency of the PVT-CPC collector, in (%)
\( \rho_p \) nanoparticle density, in \((kg/m^3)\)
\( \rho_{nf} \) nanofluid density, in \((kg/m^3)\)
\( \rho_{bf} \) basefluid density, in \((kg/m^3)\)
\( \tau_g \) solar energy fraction transmitted from top glass cover of PVT-CPC collector

SUBSCRIPTS

a ambient
\( a_n \) annual
b basin surface
E east side
e\( _n \) energy
e\( _x \) exergy
\( E_{in} \) input embodied energy
\( E_{out} \) output embodied energy
\( E_{sol} \) annual solar energy
f fluid
g\( _i \) inner condensing cover
g\( _o \) outer condensing cover
i rate of interest
n life-time period
p particle
S\( _{sl} \) solar
th thermal
v vapor
W west side

ABBREVIATIONS

BF basefluid
SS single slope solar distiller unit
FPC collector, flat plate
HE heat exchanger
HTC coefficient of heat transfer
NF nanofluid
NP nanoparticle
PVT photovoltaic thermal
R reflectors
N-PVT-CPC-SS-HE N identical photovoltaic thermal compound parabolic concentrator collectors single slope with helical coiled heat exchanger

1. INTRODUCTION

Potable water is a dire need for every creature in this world. As population and pollution are growing daily, water demand is also increasing while water resources are reducing continuously. So to fulfill the demand for potable water, work is needed in this field. Colebrook (1939) studied a particular transition area between smooth and rough surfaces for turbulent flow. Soliman (1976) recommended the concept of feeding external thermal energy from the solar collector into the basin. Rai & Tiwari (1983) analyzed the effect of mass-flow rate with a solo basin solar distillation system attached to a flat plate collector and observed a decrease in yield. Lawrence & Tiwari (1990) calculated an active solar distiller of natural type with heat exchange...
to extend the empirical formulas. They observed that the addition of a collector increases the water temperature, which improves the system’s efficiency, while increasing water depth decreases efficiency overall. Popiel & Wojtkowiak (1998) developed formulas for the thermophysical properties of water. Pak & Cho (1998) studied hydrodynamic heat transfer of dispersed fluids with oxide particles. Kumar & Tiwari (1999) optimized the active double slope solar distiller unit and got the highest water generation at a 1.8 m/s flow rate. Tiwari (2002) developed solar energy in fundamentals, design, modeling, and applications. Delyannis (2003) studied the historical developments of solar desalination taking care of energy and the environment. Tiwari et al. (2003) studied the gradual development of solar distillation systems. Boukar & Harmim (2005) explained the equations for perpendicular solar distiller units. Tiwari & Tiwari (2007) investigated experimentally and found that heat exchange was not significant at a temperature lower than 50 °C, and the amount of water was two times greater than without a heat exchanger. Hwang et al. (2007) studied experimentally and showed that water-based nanofluid in a rectangular cavity is more stable than water. Ho et al. (2008) analyzed uncertainties of thermal conductivity and viscosity in a square enclosure of natural convection. Dubey & Tiwari (2009) analyzed serially connected PVT flat plate water collectors. Gaur & Tiwari (2010) analyzed the maximum yield for four (N = 4) collectors and 50 kg mass of fluid in a hybrid solar still. Dev & Tiwari (2010) developed an equation for an active solar distiller unit (hybrid/PVT). Patel et al. (2010) investigated experimentally thermal conductivity enhancement in oxide and metallic nanofluids. Sharma et al. (2012) developed turbulent flow heat transfer coefficients of water-based nanofluids to predict friction in forced convection. Khanafar & Vafai (2011) studied a critical synthesis of thermophysical characteristics of nanofluids. Yiamsawas et al. (2012) studied specific heat of nanofluids. Khairul et al. (2013) investigated theoretically CuO, Al2O3, ZnO water-loaded nanofluids and concluded that the heat transfer coefficient increases and entropy decreases. Mahian et al. (2014a) examined solar collector performance based on micro-channels using CuO, Al2O3, TiO2, and SiO2 nanofluids and found that the output temperature follows the order CuO > Al2O3 > TiO2 > SiO2 and also observed that the generation of entropy decreases. Mahian et al. (2014b) studied water aluminum oxide nanofluids in a solar collector and various thermophysical models to find entropy. Mahian et al. (2015) studied the effects of heat transfer, pressure drop, pH, and entropy generation in a solar collector using SiO2/water nanofluids. Shyam et al. (2015) developed an expression for connected N-PVT-water collectors for temperature-dependent electrical efficiency of two different configurations in series that gave almost the same outcomes. Atheaya et al. (2015) developed a characteristic mathematical expression for a partly roofed PVT compound parabolic concentrator (CPC). Sekhar & Sharma (2015) studied specific heat and viscosity for Al2O3, ZnO nanofluids. Kabeel et al. (2014) analyzed a single slope solar distiller with a vacuum fan using water-based (Al2O3) nanofluids. Elangoo et al. (2015) analyzed the performance based on thermal energy, exergy, and productivity of a single slope solar still using different nanofluids. Shyam et al. (2016) performed experiments for validation which found good conformity in these two studies. Mwesigye et al. (2016) analyzed computationally that Al2O3 nanofluid has a greater yield for passive double slope solar distiller units. Tripathi & Tiwari (2016) studied the comparison between N-PVT-FPC and N-PVT-CPC. (MathWorks Inc 2016) MathWorks Inc., MATLAB-R2016a (9.0.0.341360) is used to compute the numerical entities. Tiwari & Sahota (2017b) analyzed in detailed review the energy and economic efficiencies of solar stills for different solar distiller units’ (passive and active) characteristic equations. Various features of the nanofluids were studied: ultrafast heat transfer, low friction coefficient, better stability, low pumping power, superior lubrication, and erosion. Mahian et al. (2017) studied in a solar distiller unit attached with heat exchanger the effects of evaporation rate using nanofluids. Saleh et al. (2017) analyzed the effect of solvent ZnO and found it effective in solar distiller units. Sahota et al. (2017) studied and gave the maximum value of the internal coefficient of evaporative heat transfer (HTCs), which gave a high rate of water generation compared with other distiller units. The characteristic curve for (N-PVT-FPC-DS-HE) was based on nanofluid. Sharshir et al. (2017) analyzed the performance of nanoparticles like copper oxide and graphite micro-flakes on solar distiller units with different cooling on a cover of toughened glass. It was concluded that solar distiller yield increased by 47.8% and 57.6% with graphite and copper oxide micro-flake combinations. Tiwari & Sahota (2017a) studied basic principles, thermal modeling, and its applications on an advanced solar distiller. Joshi & Tiwari (2018) analyzed N identical PVT-CPC single slope solar distillers. Singh et al. (2019) analyzed for a single slope partly covered PVT-FPC system the various efficiencies and depths of water under optimized conditions. Dharamveer et al. (2019) presented a review on nanofluids with an active solar distiller unit which concluded that nanofluids reduce pump work by reducing viscosity and increase water generation. Eltaweel & Abdel-Rehim (2019) studied the energy and exergy of a thermosiphon in forced-circulation mode for a flat-plate solar collector using MWCNT/water nanofluid, a case study in thermal engineering. Singh et al. (2020) analyzed energy payback time for N identical compound parabolic concentrator collectors of single-slope without nanofluid. Sharma et al. (2020) observed that the value of the exergoeconomic parameter decreases with increase in the mass-flow rate value.
analyzed energy matrices and enviro-economics for active and passive solar distiller units comparatively. Dhivagar et al. (2020) analyzed gravel coarse aggregate sensible heat storage single slope solar stills with energy, exergy, and economic assessments. Arora et al. (2020) studied incorporating carbon nanotubes using N-PVT-CPC double slope solar stills. Al-Obaidi & Mohammed (2019) numerically investigated transient flow characteristics in an axial flow pump and pressure fluctuation analysis based on the CFD technique. Al-Obaidi & Jaffal (2021) reviewed the influence of various types of twisted tape inserts on hydrodynamic, pressure drop and thermal heat performance in heat exchangers. Alhamid & Al-Obaidi (2021) investigated the flow pattern, pressure drop, and thermal performance for smooth and corrugated pipes. Al-Obaidi (2021) studied the flow structure and effect of different pump rotational speeds on a centrifugal pump’s performance experimentally and numerically. Al-Obaidi & Alhamid (2021) analyzed the flow structure, pressure drop, thermo-hydraulic performance, and improvement of heat transfer of a three-dimensional pipe with varying corrugated geometrical configurations numerically investigated using FLUENT software. Dharamveer et al. (2021) analytically studied a photovoltaic thermal (PVT) compound parabolic concentrator (CPC) active double slope solar distiller with a helically coiled heat exchanger using CuO nanoparticles, and it was found to be better than an N-PVT flat plate double slope solar still with a heat exchanger using CuO nanoparticles. However, this kind of literature is obtainable on a single active slope solar distiller unit with a helically coiled heat exchanger (N-PVT-CPC-SS-HE) using CuO nanoparticles. Table 1 shows prior research work on solar distillers based on using nanofluids.

2. SYSTEM DESCRIPTION

Figure 1 shows N identical 25% partly covered photovoltaic thermal compound parabolic concentrator collectors with a helically coiled heat exchanger active single slope solar distiller unit (N-PVT-CPC-SS-HE). Collectors are connected in series and put at an angle of 45° south-facing. A parabolic concentrator collector reflects the beam radiation which falls on the receiver area, and the radiation falls on the direct collector surface and gets absorbed. Radiation on the PV module is the cause of electricity generation, which operates the DC motor and runs the pump, and access can be utilized for other applications. The

<table>
<thead>
<tr>
<th>References</th>
<th>Systems (active and passive)</th>
<th>Conclusions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Patel et al. (2010)</td>
<td>Experimentally with solar still</td>
<td>Oxide metallic nanofluids</td>
</tr>
<tr>
<td>Khanafer &amp; Vafai (2011)</td>
<td>Solar still</td>
<td>Thermophysical characteristics of nanofluids</td>
</tr>
<tr>
<td>Yiamsawasd et al. (2012)</td>
<td>Specific heat of solar still</td>
<td>Using nanofluids</td>
</tr>
<tr>
<td>Khairul et al. (2013)</td>
<td>Solar still</td>
<td>HTCs Al₂O₃, CuO and ZnO</td>
</tr>
<tr>
<td>Mahian et al. (2014a, 2014b, 2015)</td>
<td>Different thermophysical model solar collectors</td>
<td>Al₂O₃, CuO and TiO₂, SiO₂</td>
</tr>
<tr>
<td>Sekhar &amp; Sharma (2015)</td>
<td>Solar still</td>
<td>Viscosity and specific heat Al₂O₃</td>
</tr>
<tr>
<td>Kabeel et al. (2014)</td>
<td>Single slope solar still</td>
<td>116% with Al₂O₃ with vacuum</td>
</tr>
<tr>
<td>Elango et al. (2015)</td>
<td>Single slope basin solar still</td>
<td>29.5% with Al₂O₃, 18.63% Fe₂O₃ and 12.67% with ZnO</td>
</tr>
<tr>
<td>Mwesigye et al. (2016)</td>
<td>Passive solar still</td>
<td>Al₂O₃</td>
</tr>
<tr>
<td>Tiwari &amp; Sahota (2017b)</td>
<td>Passive double slope solar distillers</td>
<td>42.72% CuO, 45.23% Al₂O₃ and 39.74% TiO₂</td>
</tr>
<tr>
<td>Mahian et al. (2017)</td>
<td>With heat exchanger solar collector</td>
<td>CuO nanofluid</td>
</tr>
<tr>
<td>Saleh et al. (2017)</td>
<td>Solar distiller</td>
<td>With ZnO</td>
</tr>
<tr>
<td>Sahota et al. (2017)</td>
<td>Single and double with Hx</td>
<td>With CuO, Al₂O₃ and TiO₂</td>
</tr>
<tr>
<td>Sharshir et al. (2017)</td>
<td>Passive solar distiller</td>
<td>With CuO and graphite</td>
</tr>
<tr>
<td>Joshi &amp; Tiwari (2018)</td>
<td>Active single slope with helically coiled Hx</td>
<td>Without nanofluids</td>
</tr>
<tr>
<td>Eltaweel &amp; Abdel-Rehim (2019)</td>
<td>Flat plate collector</td>
<td>MWCNT/water nanofluid</td>
</tr>
<tr>
<td>Arora et al. (2020)</td>
<td>Using helically coiled Hx active double slope solar still</td>
<td>Using carbon nanotubes</td>
</tr>
<tr>
<td>Al-Obaidi &amp; Mohammed (2019)</td>
<td>Active double slope with helically coiled Hx</td>
<td>With CuO nanoparticles</td>
</tr>
<tr>
<td>Present study</td>
<td>Active single slope with helically coiled Hx</td>
<td>With CuO nanoparticles</td>
</tr>
</tbody>
</table>
specifications and other components of the proposed system are given in Table 2. The system is oriented south-facing at an inclination angle of the glass cover of 30° to the horizontal. Maximum solar radiation falls on the glass cover absorbed by the basin liner. Through the heat exchanger, the nanoparticles exchange heat to the basin fluid. It is found in a literature survey that the helically coiled heat exchanger is more effective than a simple tube heat exchanger. The CuO nanoparticles exchange more heat as found in the literature due to having more heat-absorbing capacities. The nanoparticles cover more surface area in a single slope solar distiller unit with a heat exchanger, and volume increases basin fluid temperature. Getting thermal energy by the combination of single slope solar distiller unit, by absorbing heat due to solar radiation, externally from PVT-CPC collectors and nanoparticles via a heat exchanger enhances the temperature of the solar distiller unit. Finally, the vapor droplets condense by realizing the latent heat, and these are collected at the lower ends of the inclined glass cover of the basin.

The proposed hybrid system generates potable water as well as electricity. This kind of system requires low maintenance and can be installed easily at a small and large scale to fulfill the demand for potable water for domestic and industrial purposes. In the present paper, we emphasize the production of maximum potable water, so CPC collectors partly covered with a PV portion have been considered.

The proposed system is compared with the previous system (as shown in Figure 2) based on the temperature of the basin water, the temperature of the glass cover inside, the temperature of the fluid outlet from the N-CPC collectors, overall thermal energy, overall thermal exergy, electrical exergy, and yield. The possibility of nanoparticle sedimentation is higher in water. Therefore the critical value of the size of nanoparticles leads to change in aggregation. Further, this can be removed by using sophisticated and advanced types of equipment.

However, to extract out this problem, some separation methods, i.e., electrophoresis, centrifugation, filtration, and chemical methods, can be used. Tables 2–4 show specifications, thermophysical properties of nanoparticles, and mean velocity of air.

3. THERMAL MODELING

All modes of heat transfer to be considered for thermal modeling and different system components express them in the form of balancing equations. To develop the characteristic equation, the following assumptions by Sharshir et al. (2017) are made as below:
Table 2 | Parameters and specifications used in active single slope solar distiller N-PVT-CPC-SS-HE

<table>
<thead>
<tr>
<th>Components</th>
<th>Specifications</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Specifications for single slope distiller</strong> (Singh et al. 2019)</td>
<td></td>
</tr>
<tr>
<td>Length of basin</td>
<td>2 m</td>
</tr>
<tr>
<td>Width of basin</td>
<td>1 m</td>
</tr>
<tr>
<td>Glass cover inclination</td>
<td>15°</td>
</tr>
<tr>
<td>Body material</td>
<td>FRP (fiber-reinforced plastic)</td>
</tr>
<tr>
<td>Stand material</td>
<td>MS</td>
</tr>
<tr>
<td>Condensing cover</td>
<td>Glass</td>
</tr>
<tr>
<td>Orientation</td>
<td>South</td>
</tr>
<tr>
<td><strong>Helically coiled heat exchanger</strong> (Dhivagar et al. 2020)</td>
<td></td>
</tr>
<tr>
<td>Number of turns</td>
<td>12</td>
</tr>
<tr>
<td>Length of heat exchanger</td>
<td>1.937 m</td>
</tr>
<tr>
<td>Dia. of coil tube</td>
<td>0.0125 m</td>
</tr>
<tr>
<td>Coil dia.</td>
<td>0.045 m</td>
</tr>
<tr>
<td><strong>Specifications for CPC collectors</strong></td>
<td></td>
</tr>
<tr>
<td>Specific heat</td>
<td>4,200</td>
</tr>
<tr>
<td>$K_b$</td>
<td>0.78 W/(m·K)</td>
</tr>
<tr>
<td>$L_b$</td>
<td>0.003 m</td>
</tr>
<tr>
<td>$K_i$</td>
<td>0.166 W/(m·K)</td>
</tr>
<tr>
<td>$L_i$</td>
<td>0.1 m</td>
</tr>
<tr>
<td>$U_{tc,p}$</td>
<td>2.67 W/(m²·K)</td>
</tr>
<tr>
<td>$U_{tc,a}$</td>
<td>19.34 W/(m²·K)</td>
</tr>
<tr>
<td>$PF_1$</td>
<td>0.12</td>
</tr>
<tr>
<td>$PF_2$</td>
<td>0.58</td>
</tr>
<tr>
<td>$h_{pf}$</td>
<td>100 W/(m²·K)</td>
</tr>
<tr>
<td>$h_i$</td>
<td>2.8 W/(m²·K)</td>
</tr>
<tr>
<td>$\rho$</td>
<td>0.84</td>
</tr>
<tr>
<td>$\tau_b$</td>
<td>0.95</td>
</tr>
<tr>
<td>$\alpha_p$</td>
<td>0.6</td>
</tr>
<tr>
<td>$\beta_c$</td>
<td>0.8</td>
</tr>
<tr>
<td>$\alpha_c$</td>
<td>0.7</td>
</tr>
<tr>
<td>$\alpha_p$</td>
<td>0.6</td>
</tr>
<tr>
<td>$\eta_0$</td>
<td>0.15</td>
</tr>
<tr>
<td>$F$</td>
<td>0.96</td>
</tr>
<tr>
<td>Length of copper tubes</td>
<td>1 m</td>
</tr>
<tr>
<td>Dia. of tube</td>
<td>0.0125 m</td>
</tr>
<tr>
<td>CPC thickness</td>
<td>0.004 m</td>
</tr>
<tr>
<td>CPC angle to horizontal</td>
<td>30°</td>
</tr>
<tr>
<td>Area of aperture</td>
<td>2 m²</td>
</tr>
<tr>
<td>Module’s aperture area</td>
<td>0.5, 2 and 0 m²</td>
</tr>
<tr>
<td>Module’s receiver area</td>
<td>0.25, 1 and 0 m²</td>
</tr>
<tr>
<td>Area of receiver</td>
<td>1 m²</td>
</tr>
<tr>
<td>Receiver’s aperture area</td>
<td>1.5, 0 and 2 m²</td>
</tr>
<tr>
<td>Receiver’s collector area</td>
<td>0.75, 0 and 1 m²</td>
</tr>
</tbody>
</table>

(Continued.)
i. The level of water is constant.
ii. In solar cells, ohmic losses are neglected.
iii. There is no vapor leakage from the solar distiller unit.
iv. Film condensation is over the entire surface of the glass.
v. A quasi-static state applies for the partly covered active solar distiller unit.

3.1. System-A: active single slope $N$ identical hybrid (N-PVT-CPC) solar distiller units with heat exchanger

3.1.1. For the different components' energy balance equations (Tiwari & Sahota 2017a)

a. Energy balance for semi-transparent PV module:

$$\rho \alpha \tau g \beta I_o A_{rm} = [U_{ic,a}(T_c - T_a) + U_{ic,p}(T_c - T_p)]A_{rm} + \rho \eta_m I_o A_{sm}$$

$$1$$

Table 2 | Continued

<table>
<thead>
<tr>
<th>Components</th>
<th>Specifications</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type of collectors</td>
<td>Tube and plate type</td>
</tr>
<tr>
<td>Number of collectors</td>
<td>4</td>
</tr>
<tr>
<td>No. of solar cells</td>
<td>36</td>
</tr>
<tr>
<td>Area of solar cell</td>
<td>0.007 m$^2$</td>
</tr>
<tr>
<td>DC motor</td>
<td>12 V, 25 W</td>
</tr>
</tbody>
</table>

Nanoparticle specifications (Dhivagar et al. 2020)

<table>
<thead>
<tr>
<th>Nanoparticles</th>
<th>CuO</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density</td>
<td>$6.3 \times 10^3$ kg/m$^3$</td>
</tr>
<tr>
<td>Thermal conductivity</td>
<td>17.6 W/(m K)</td>
</tr>
<tr>
<td>Specific heat</td>
<td>550 J/(kg K)</td>
</tr>
</tbody>
</table>

Figure 2 | Active double slope distiller $N$-identical 25% enclosed PVT-FPC-HE collectors.
b. Energy balance for an absorber plate below the PV module:

\[
\rho_p \alpha_p \tau_g^2 (1 - \beta_p) I_{Am} + U_{lc,p}(T_c - T_p) = [U_{lc,s}(T_p - T_w)A_{rm} + F/h_{pl}(T_p - T_w)]A_{rm}
\]

(2)

c. Energy balance for fluid flowing below absorber:

\[
m_tC_i \frac{dT_i}{dx} = F/h_{pl}(T_p - T_w)bdx
\]

(3)

d. Basin liner:

\[
a_b I_b A_b = h_{bw}(T_b - T_w)A_b + h_{lw}(T_b - T_w)A_b
\]

(4)

e. Inside and outside glass cover:

\[
h_{kg}(T_{gi} - T_{go})A_g = h_1(T_{go} - T_w)A_g
\]

(5)

\[
a_g I_b A_g = h_2(T_w - T_{gi})A_b + h_{kg}(T_{gi} - T_{go})A_g
\]

(6)

f. For mass of basin water:

\[
Q_{aw} + \alpha_w I_b A_b + h_{bw}(T_b - T_w)A_b = m_tC_i \frac{dT_i}{dx} + h_2(T_w - T_{gi})A_b
\]

(7)

**Table 3 | Thermophysical properties of CuO nanoparticles**

<table>
<thead>
<tr>
<th>Property</th>
<th>Formula</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density</td>
<td>( \rho_{df} = \rho_p + (1 - \rho_p)\rho_{id} )</td>
</tr>
<tr>
<td>Thermal expansion</td>
<td>( \beta_{df} = \beta_p + (1 - \beta_p)\beta_{id} )</td>
</tr>
<tr>
<td>Coefficient</td>
<td>( \kappa_{df} = \kappa_p \left[ 0.9843 + (0.398)(\beta_p)^{0.467} \left( \frac{\rho_{df}}{\rho_p} \right)^{0.0235} \left( \frac{1}{d_p(nm)} \right)^{0.2246} - (3.951) \left( \frac{\rho_p}{\kappa_{df}} \right) + (34.034) \left( \frac{\rho_p}{\kappa_{df}} \right)^2 \right] )</td>
</tr>
<tr>
<td>Viscosity</td>
<td>( \mu_{df} = (2.41 \times 10^{-5})10^{\frac{d_p}{150nm}} )</td>
</tr>
<tr>
<td>Specific heat</td>
<td>( C_{df} = 0.8429 \left( 1 + \frac{T_{df}}{50} \right)^{-0.3037} \left( 1 + \frac{\rho_p}{100} \right)^{2.272} \left( 1 + \frac{d_p}{50} \right)^{0.4167} )</td>
</tr>
</tbody>
</table>

0 < \( \rho_p < 10\% \); 20 < \( T_{df} < 70\;^\circ C \); 11 < \( d_p < 150\;\text{nm} \) (CuO–water)

**Table 4 | Average air velocity**

<table>
<thead>
<tr>
<th>Month</th>
<th>Jan</th>
<th>Feb</th>
<th>Mar</th>
<th>Apr</th>
<th>May</th>
<th>Jun</th>
<th>Jul</th>
<th>Aug</th>
<th>Sep</th>
<th>Oct</th>
<th>Nov</th>
<th>Dec</th>
</tr>
</thead>
<tbody>
<tr>
<td>Velocity (m/s)</td>
<td>2.77</td>
<td>3.13</td>
<td>3.46</td>
<td>3.87</td>
<td>4.02</td>
<td>4.11</td>
<td>3.39</td>
<td>2.91</td>
<td>2.85</td>
<td>2.16</td>
<td>1.83</td>
<td>2.4</td>
</tr>
</tbody>
</table>

Table 4 | Average air velocity

Water Supply Vol 22 No 2, 1314

Downloaded from http://iwaponline.com/ws/article-pdf/22/2/1306/1009685/ws022021306.pdf by guest on 03 March 2022
g. Energy balance equation for helically coiled heat exchanger immersed in the basin of a single slope solar distiller unit (Dharamveer et al. 2021):

\[ m_t C_f \frac{dT_i}{dx} = -2 \pi r_i U(T_{wi} - T_w) \]  \hspace{1cm} (8)

Applying boundary conditions:

\[ T_w(x = 0) = T_{woN} \quad \text{and} \quad T_w(x = L) = T_{wi} \]

\[ T_{wi} = T_{woN} \exp \left( - \frac{2 \pi r_i UL}{m_t C_f} \right) + T_w \left(1 - \exp \left( -\frac{2 \pi r_i UL}{m_t C_f} \right) \right) \]  \hspace{1cm} (9)

where

\[ U = \left[ \frac{1}{h_w} + \frac{r_1}{K_1} \log \left( \frac{r_2}{r_1} \frac{1}{h_w} \right) \right]^{-1} \]  \hspace{1cm} (10)

\[ T_{woN} = \left[ \frac{(AF_R(\sigma_1))(1 - K_p^N)}{m_t C_f(1 - K_p)} \right] I_b + \left[ \frac{(AF_R(UL_1))(1 - K_p^N)}{m_t C_f(1 - K_p)} \right] T_a + T_{wi} K_m^N \]  \hspace{1cm} (11)

By solving Equations (9) and (11) we get:

\[ T_{woN} = \left[ \left[ \frac{(AF_R(\sigma_1))(1 - K_p^N)}{m_t C_f(1 - K_p)} \right] \frac{1}{1 - e^{K_m^N}} \right] I_b + \left[ \frac{(AF_R(UL_1))(1 - K_p^N)}{m_t C_f(1 - K_p)} \right] \left( \frac{1}{1 - e^{K_m^N}} \right) T_a + T_{HE} \left( \frac{1 - e^N}{1 - e^{K_m^N}} \right) \]  \hspace{1cm} (12)

Now the heat energy gain is computed using the following relation for N-PVT-CPC-SS-HE:

\[ Q_{aN} = m_t C_f (T_{woN} - T_{wi}) \]  \hspace{1cm} (13)

From Equations (11) and (12) the water output temperature of the N-PVT-CPC collector is:

\[ T_{HE} > T_{wi} > T_w \]

\[ Q_{aN} = \left[ \left[ \frac{(AF_R(\sigma_1))(1 - K_p^N)}{1 - e^{K_m^N}} \right] I_b + \left[ \frac{(AF_R(UL_1))(1 - K_p^N)}{1 - e^{K_m^N}} \right] \left( \frac{1}{1 - e^{K_m^N}} \right) T_a + T_{HE} \left( \frac{1 - e^N}{1 - e^{K_m^N}} \right) \right] \]

\[ + m_t C_f \left( T_{HE} \left( \frac{1 - e^N}{1 - e^{K_m^N}} \right) - T_{wi} \right) \]  \hspace{1cm} (14)

\[ Q_{aN} = [D_1 I_b + D_2 T_a + D_3] \]

where the unknown terms \((AF_R(\sigma_1)), (AF_R(UL_1)), D_1, D_2 \text{ and } D_3\) are given in the Supplementary Information.

The first-order equation can be used for solution

\[ \frac{dT_w}{dt} + a_2 T_w = f_2(t) \]  \hspace{1cm} (15)

where \(a_2\) is \(U_l/(M_t C_f)\).

The first-order differential equation can be written as:

\[ T_w = \frac{f(\theta)}{a_1} \left( 1 - \frac{\exp (-a_1 \theta)}{a_1 \theta} \right) + T_{wi} \frac{1 - \exp (-a_1 \theta)}{a_1 \theta} \]  \hspace{1cm} (16)
Solving Equations (5) and (6) with the help of Equation (15) and substituting the values of $T_{gi}$, $T_b$ and $Q_{uN}$ we get:

$$T_w = \frac{f(\theta_2)}{a_1} (1 - \exp(-a_2 \Delta t)) + T_{wo} \exp(-a_2 \Delta t)$$  \hspace{1cm} (17)

The 0.933 is used as the solar radiation exchange constant for exergy. Hourly water generation of the proposed system can be calculated by the mentioned equation:

$$M_w = \frac{q_{cw}}{L_v} \times 3,600 = \frac{h_{ew} A_b (T_w - T_{gi})}{L_v} \times 3,600$$  \hspace{1cm} (18)

where the latent heat of vaporization is expressed as (Tiwari 2002):

$$L_v = 3.1625 \times 10^6 + [1 - (7.616 \times 10^{-4} \times T_v)] \quad \text{for} \quad T_v > 70 \, ^{\circ}C$$

$$L_v = 2.4935 \times 10^6 + [1 - (9.4779 \times 10^{-4} \times T_v) + (1.3132 \times 10^{-7} \times T_v^2) - (4.7974 \times 10^{-3} \times T_v^3)] \quad \text{for} \quad T_v < 70 \, ^{\circ}C$$

where the unknown terms $a_2$, $T_w$, $T_{go}$, $T_{gi}$, $C_1$ and $S$ are given in the Supplementary Information.

$$E_{\text{hourlyEn}} = h_{1w} (T_w - T_{gi}) A_b$$  \hspace{1cm} (19)

$$E_{\text{hourlyEx}} = h_{1w} \left[ (T_w - T_{go}) - (T_a + 273) \ln \left( \frac{T_w + 273}{T_{gi} + 273} \right) \right] A_b$$  \hspace{1cm} (20)

Per-hour variation in water temperature, thermal energy, thermal exergy, and distillate output have been obtained using Equations (16) and (18)–(20), respectively.

### 4. METHODOLOGY

The present study is based on climatic conditions of types of days (a), (b), (c), and (d) in New Delhi, India. Data used for calculation is taken from IMD, Pune, India. The temperature of the glass cover and PVT surfaces on collectors are calculated using the Liu–Jordan formula. The hourly variations in radiant energy and ambient temperature are shown in Figure 4. The procedure adopted for computing the proposed system based on 0.25% concentration of CuO nanoparticles is performed for $N = 4$, mass-flow rate 0.02 kg/s, and 280 kg mass of basin fluid. For numerical computation, the MATLAB-R2016a software is used. The following steps are adopted in the methodology to carry out the study of the proposed system:

**Step-I**
Firstly the Liu–Jordan formula (Tiwari 2002), solar radiation ($I_b$) and global irradiation ($I_s$) are used to calculate for the proposed system (N-PVT-CPC-SS-HE) for the year. Further per day solar radiation is given with the number of days according to (a) clear days, (b) hazy days, (c) hazy and cloudy days and (d) cloudy days in a month.

**Step-II**
All the parameters are optimized to maximize the collector’s output temperature, and the basin water temperature is computed on an hourly, monthly, and annual basis.

**Step-III**
Later on, thermal energy and thermal exergy and hourly, daily, and monthly yield are given according to (a) clear days, (b) hazy days, (c) hazy and cloudy days and (d) cloudy days.

**Step-IV**
The proposed system is compared based on numerically computed values with the previous system. To easily understand the procedure, the flow chart is shown as Figure 3.
5. RESULTS AND DISCUSSION

In the proposed study, the analytical calculation is done for May. The per-hour variation in solar intensity in W/m² and ambient temperature is shown in Figure 4. The average air velocity in May is 4.02 m/s.

Figure 5 shows the per-hour variation in basin water temperature in °C for the proposed system at \( N = 4 \), fluid-flow rate 0.02 kg/s and depth of water 0.14 m, for a-type days by month. The value of basin water temperature \( (T_w) \) is lower than the value of the \( N \)th collector's outlet temperature \( (T_{wu}) \). This happens because basin water is fed to the first collector through the DC motor pump. Later on, the inside-glass temperature is lower than the value of the basin water temperature. This is due to the glass surface being in contact with the atmosphere, so its heat losses are due to convection and radiation followed by conduction.

Figure 6 shows the monthly variation in basin water temperature in °C vs yield in kg for the proposed system at \( N = 4 \); fluid-flow rate is 0.02 kg/s and depth of water 0.14 m. The graph shows that the value of the yield rises with rising temperature. In the summer season, March, April, and May, it has a higher value corresponding to a rise in basin water temperature, and a very similar pattern follows in August, September, and October. The maximum yield occurs in May, corresponding to the maximum basin water temperature, and minimum yield occurs in December, corresponding to the minimum temperature.

Figure 3 | A flow chart to show the procedure adopted.
Figure 7 shows per-hour variation in collector outlet temperature ($T_{\text{woN}}$) in °C for the proposed system at $N = 4$; the fluid-flow rate is 0.02 kg/s and depth of water 0.14 m, by month. It is found that the maximum temperature occurs in the daytime from 12.00 pm to 3.00 pm and the minimum outside this time. The maximum collector outlet temperature ($T_{\text{woN}}$) in °C is in March and the minimum in December.
Figure 8 shows the comparison of collector outlet temperature \( T_{\text{woN}} \) in °C vs yield in kg for the proposed system at \( N = 4 \); the fluid-flow rate is 0.02 kg/s and the depth of water 0.14 m. It is found that the value of the yield rises with rising temperature. In the summer season, March, April, and May, it has a higher value corresponding to a rise in collector outlet temperature, and very similar patterns follow in August, September, and October. The maximum yield occurs in May, corresponding to the maximum collector outlet temperature, and low yield values in July, August, in the summer, and December, January in the winter season. The minimum yield occurs in December corresponding to the minimum temperature.

Figure 9 shows per-hour variation in inside-glass temperature \( T_{\text{gi}} \) in °C for the proposed system at \( N = 4 \); the fluid-flow rate is 0.02 kg/s and depth of water 0.14 m, by month. The graph follows almost the same pattern for all months. It appears that
the inside-glass temperature is always lower than the basin water temperature. This happens so the glass surface being in contact with ambient air due so that heat losses occur. Here, the rate of evaporation is determined by the temperature differences between the basin water temperature ($T_w$) and inside-glass temperature ($T_{gi}$). The evaporative heat transfer coefficient is inversely proportional to ($T_w - T_{gi}$), while the convective and radiative heat transfer coefficients are responsible for heat loss. Therefore high yield is possible when the evaporative heat transfer coefficient is high.

**Figure 8** | Monthly variation in mean collector outlet water temperature in °C vs yield in kg.

**Figure 9** | Hourly variation of inside-glass temperature in °C by month on a-type days.
Figure 10 represents the hourly variation of different temperatures of the proposed system at \( N = 4 \); the fluid-flow rate is 0.02 kg/s, and the depth of water 0.14 m, for type-a days in May. It is found that the value of the collector outlet temperature \( (T_{woN}) \) in °C is lower than the value of the basin water temperature in °C. The output of the basin is fed as input to the first collector with the help of a pump, and then the input of the second collector is the output of the first collector, followed by all four collectors. The output of the fourth collector is fed to the basin. Further, the inside-glass temperature is lower than the value of the basin water temperature \( (T_w) \). This is due to the glass surface being in contact with the atmosphere, so its heat losses are due to convection and radiation followed by conduction. Solar cells are attached to the collector top surface, so their temperature also decreases due to convection by ambient air. It is found that the watt peak of photovoltaics in the case of the partly covered N-PVT-CPC with single slope still using a heat exchanger is kept the same. The electrical exergy is found to be the same for the N-PVT-FPC double slope solar still using a heat exchanger.

Figure 11 shows the variation of average thermal exergy of the proposed system at \( N = 4 \); the fluid-flow rate is 0.02 kg/s, and the depth of water 0.14 m. The graph represents thermal exergy vs basin water temperature by month. It is clear from the figure that for May it has the highest value, and in the pre-monsoon in March, April, and May, the thermal exergy is increasing with the temperature of basin water as well as in the post-monsoon in September, October, while in other months it is decreasing and in February it has the lowest value. As the trend of the graph shows, the thermal exergy decreases with decreases in basin water temperature and increases vice versa, which is apparent from the April and September months up to an optimum level.

Figure 12 shows the electrical exergy of the proposed system at \( N = 4 \); the fluid-flow rate is 0.02 kg/s and the depth of water 0.14 m. The graph represents thermal exergy by month for the same basin area compared with the previous research. The result shows that the influence of CuO nanoparticles in the helically coiled heat exchanger does not affect electricity generation due to the photovoltaic thermal plate attached to the system. The average electrical exergy for the proposed system is significantly higher than for the already existing system, and the results appear as: 11.22 kWh/month (Jan), 12.38 kWh/month (March), and 12.08 kWh/month (Oct), with 12.38 kWh/month (maximum) and 6.93 kWh/month (minimum), which depend on the covering of the photovoltaic thermal system, which is 25% in the previous and the proposed system.

Figure 13 represents the average value of potable water generation by month in kg for the proposed system at \( N = 4 \); the mass-flow rate is 0.02 kg/s and the depth of water 0.14 m. It is observed that the average yield of the proposed system is higher than the previous system. This occurs due to a higher amount of radiant energy being permitted to fall on the partly covered N-PVT-CPC.

**Figure 10** | Hourly variation in temperatures in °C \( (T_{w}, T_{gi}, T_{woN}, T_{cN}, \text{and } T_{a}) \) for a-type days in May.
identical photovoltaic compound parabolic concentrator collectors’ receiver surface. Therefore the amount of heat added in the proposed system (N-PVT-CPC-SS-HE) compared with the previous system (N-PVT-FPC-DS-HE) is higher.

Figure 14 represents a comparative analysis of the proposed system and previous research (Sahota et al. 2017). The comparison reveals that the performance of the proposed system is much better than that of the previous research. The proposed system uses CuO nanoparticles, annual yield 3,615.05 kg, and the previous system (Sahota et al. 2017) analyzed on CuO, Al₂O₃ and TiO₂ nano fluids, and water, gave annual yields of 3,250.99, 3,084.4, 2,863.33, and 2,735.11 kg, respectively. The enhancement in the percentage of the proposed system yield from the previous system is 11.19%, 17.2%, 26.25%, and
32.17%, respectively. Table 5 shows the numerical representation in comparative form for the proposed and previous systems based on yield.

Table 5 represents enhancement in the daily thermal energy and thermal exergy of the proposed and previous systems using CuO nanoparticles.

It is found that daily enhancement in thermal energy of the proposed system with CuO nanoparticles compared with the previous system with various CuO, Al2O3 and TiO2 nanofluids, and water, are found to be 16.75%, 51.13%, 61.82%, and 80.67% more significant correspondingly. The thermal exergy of the proposed system with CuO nanoparticles is more
significant than the previous system with various nanofluids by 16.08% for TiO₂, and 20% greater for water and 23.16%, 3.93% less than for CuO, Al₂O₃ respectively.

Table 6 represents enhancement in annual yield, obtained by the proposed system and previous systems using CuO nanoparticles (Sahota et al. 2017).

The enhancement in yield of the proposed system obtained for CuO nanoparticles is greater than in the previous system with CuO by 11.19%, Al₂O₃ 17.2%, TiO₂ 26.25%, and water 32.17%. The electrical exergy is almost the same as the previous system.

6. CONCLUSIONS
The proposed system has been studied based on the temperature of the basin, collector outlet temperature, cell temperature, thermal energy, exergy, electrical exergy, and yield to be higher using CuO nanoparticles in the order CuO > Al₂O₃ > TiO₂ > water. Moreover, the proposed system is better than the previous system. The temperature differences are also found to be better than in the previous study.

The proposed system uses CuO nanoparticles, with an annual yield of 3,615.05 kg, which is greater than in the previous research. These results can be further improved by increasing the coverage area by 50%, 75%, and 100% photovoltaic thermal compound parabolic concentrator. The proposed system can generate a sufficient amount of electricity used to operate the pump’s motor to circulate water, and the rest can be stored for further use when there is no sunlight. So this system is called self-sustainable.

7. FUTURE SCOPE
The energy matrices, enviro-economics and exergoeconomics assisted with different nanoparticles and nanofluids can be studied. The effect of mass-flow rate, size, and shape of nanoparticles can be investigated. PCM materials can also be used to store energy in the daytime when the sun is shining, which can be further utilized when the sun is absent.
DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

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