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Thermo-economic analysis of an integrated solar power generation system using nanofluids

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HIGHLIGHTS

- Develop a thermo-economic analysis of an integrated solar-power generation system.
- A thermodynamic optimization is proposed to maximize system performance.
- Select the optimum nanofluid to replace conventional heating fluids inside a PTSC.
- Study the effect of thermal energy storage on performance and cost of the system.
- Perform monthly and daily analyses to analyze system behavior using nanofluids.

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ABSTRACT

In this paper, a thermo-economic analysis of an Integrated Solar Regenerative Rankine Cycle (ISRRC) is performed. The ISRRC consists of a nanofluid-based Parabolic Trough Solar Collector (PTSC), and a Thermal Energy Storage System (TES) integrated with a Regenerative Rankine Cycle. The effect of dispersing metallic and non-metallic nanoparticles into conventional heating fluids on the output performance and cost of the ISRRC is studied for different volume fractions and for three modes of operation. The first mode assumes no storage, while the second and the third assume a storage system with a storage period of 7.5 h and 10 h respectively. For the modes of operation with the TES, the charging and discharging cycles are explained. The results show that the presence of the nanoparticles leads to an increase in the overall energy produced by the ISRRC for all modes of operation, causing a decrease in the Levelized Cost of Electricity (LEC), and an increase in the net savings of the ISRRC. After comparing the three modes of operation, it is established that the existence of a storage system leads to a higher power generation, and a lower LEC; however, the efficiency of the cycle drops. It is seen that the maximum increase in the annual energy output of the ISRRC caused by the addition of Cu nanoparticles to Syltherm 800 is approximately 3.1%, while the maximum increase in the net savings is about 2.4%.

1. Introduction

Conventional power generation plants running on fossil fuels have been struggling recently to equate the increasing daily demand in electricity and energy from different sectors. Fossil fuels are being depleted at an exponentially increasing rate, and are set to be completely exhausted within the next 40 years as the world demand is exceeding the annual production rate. In addition, the combustion of the burning fuels releases gases that are harmful to the atmosphere and that contribute to global warming. As a result, a renewable source of energy is needed to run the power generation plants in order to save the environment and match the increasing electrical load. Solar energy provides a clean, reliable and uninterrupted source of energy that can replace or support the conventional power generation methods. Different technologies are present for harvesting the sun's energy, but the Concentrated Solar Power (CSP) technology is the most effective for power generation plants. In the CSP, the sun rays are concentrated on a specific area in order to heat the fluid. Numerous CSP methods are available, such as the Parabolic Trough Solar Collector (PTSC), Solar Power Tower (SPT), Linear Fresnel Reflector (LFR), and Parabolic Dish System (PDS). The PTSCs are the leading CSP technology due to their relatively cheap cost and high power output. However, the low efficiency and high Levelized Cost of Electricity (LEC) are two major drawbacks of using the PTSC. Numerous researchers worked on enhancing the performances of the PTSC [1–7]; consequently, the PTSC is the most commercially available

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Nomenclature

Symbols

A_a	reflective aperture area (m^2)
A_c	glass cover area (m^2)
A_r	receiver area (m^2)
$C_{Al_2O_3}$	alumina nanoparticles price (US$/g)
C_{Cu}	copper nanoparticles price (US$/g)
C_{el}	electricity sale price (US$/kWh)
C_p	specific heat capacity (kJ/kg K)
C_{SWCNT}	Single Walled Carbon Nanotubes price (US$/g)
D_{ci}	glass cover inner diameter (mm)
D_{co}	glass cover outer diameter (mm)
D_{ri}	absorber tube inner diameter (mm)
D_{ro}	absorber tube outer diameter (mm)
f	friction factor (–)
h	enthalpy (kJ/kg)
I_B	normal beam radiation (W/m^2)
i	loan interest rate (%)
k	thermal conductivity (W/m K)
L	length of collector assembly (m)
L_c	collector length (m)
l_s	*SWCNT* length (nm)
$\dot{m}_f$	fluid mass flow rate (kg/s)
$\dot{m}_s$	steam mass flow rate (kg/s)
N_c	number of collectors (–)
N_l	number of loops (–)
N_m	number of modules (–)
P	pressure (kPa)
P_c	condenser pressure (bar)
P_f	feed water pressure (bar)
P_{st}	steam turbine pressure (bar)
$\dot{Q}_{PTSC}$	power generated by the PTSC (kW)
q_c	specific heat rejected (kW/kg)
R_e	Reynolds number (–)
r_{ins}	insurance rate (%)
T	fluid temperature (°C)
t_{opt}	operating hours of the plant (h/year)
V	velocity (m/s)
v	specific volume (m^3/kg)
w	collector width (m)
w_{cp}	specific condenser pump work (kW/kg)
w_{fp}	specific feed pump work (kW/kg)
w_p	specific pump work (kW/kg)
w_{st}	specific turbine work (kW/kg)
$\dot{W}_{net}$	net power output (MW)
$\dot{W}_{pump}$	pumping power (W)
y	flash factor (–)
y_{con}	construction years of the plant (years)
y_{dec}	decommissioning years of the plant (years)
y_{opt}	plant life time cycle (years)
Z_C	capital investment cost of the condenser (US$)
Z_{CE}	capital investment cost of the civil engineering works (US$)
Z_{con}	cost of contingency issues (US$)
Z_{ct}	capital investment cost of the cooling tower (US$)
Z_{dec}	cost of decommissioning the plant (US$)
Z_{eq}	equipment capital investment cost (US$)
$Z_{eq,ins}$	equipment installation capital investment cost (US$)
Z_{FW}	capital investment cost of the feed water heater (US$)
$Z_{HE,1}$	capital investment cost of the heat exchanger between the PTSC Field and the TES system (US$)
$Z_{HE,2}$	capital investment cost of the heat exchanger between the TES and the power block (US$)
Z_{ic}	cost of indirect factors (planning, permitting) (US$)
Z_{opt}	maintenance cost of the plant (US$)
Z_{PCST}	capital investment cost of the cold storage tank pump (US$)
Z_{PFWH}	capital investment cost of feed pump (US$)
Z_{PHTF}	capital investment cost of the heating fluid pump (US$)
Z_{PHST}	capital investment cost of the hot storage tank pump (US$)
Z_{PW}	capital investment cost of the water pump (US$)
Z_{PTSC}	capital investment cost of the PTSC field (US$)
Z_{sc}	capital investment cost of the steam condenser (US$)
Z_{st}	capital investment cost of the steam turbine (US$)
$Z_{st,aux}$	capital investment cost of the auxiliary equipment of the steam turbine (US$)
Z_{wt}	capital investment cost of the water treatment facility (US$)

Greek symbols

α_c	glass cover absorptance (–)
α_r	receiver absorptance (–)
γ	nanolayer thickness ratio (–)
ε_c	glass cover emissivity
ε_r	receiver emissivity
η_{ISRRC}	energetic efficiency of the ISRRC (%)
η_{st}	isentropic efficiency of the steam turbine (%)
η_p	isentropic efficiency of the pump (%)
η_r	receiver efficiency (–)
η_o	collector optical efficiency (%)
μ	dynamic viscosity (mPa s)
ν	kinematic viscosity (mm^2/s)
ρ	density (kg/m^3)
ρ_{cl}	mirror reflectance
τ_c	glass cover transmittance
φ	volume fraction (%)

Subscripts

Al_2O_3	alumina nanoparticles
C_u	copper nanoparticles
f	fluid
n	nanoparticles
nf	nanofluids
SWCNT	Single Walled Carbon Nanotubes
sy	Syltherm 800
th	Therminol VP-1

Abbreviations

CNT	Carbon Nanotubes
CSP	Concentrated Solar Power
ISRRC	Integrated Solar Regenerative Rankine Cycle
LEC	Levelized Cost of Electricity
NPV	Net Present Value
NS	Net Savings
PTSC	Parabolic Trough Solar Collector
SAM	System Advisory Model
SWCNT	Single Walled Carbon Nanotubes
TES	Thermal Energy Storage

solar technology for power generation plants. The performance of PTSCs power generation plants is studied by multiple researchers.

Reddy et al. [8] studied the energetic and exergetic performances of a solar thermal power plant system in the cities of Delhi