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Analytical characteristic equation of nanofluid loaded active double slope solar still coupled with helically coiled heat exchanger

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ABSTRACT

Nanofluids are embryonic fluids and promising thermal energy carrier in solar thermal applications due to their superior thermo-physical and optical properties. In present communication, an analytical expression of the characteristic equation of two different systems viz. (A) active double slope solar still coupled with series connected partially covered N photovoltaic thermal flat plate collectors (N-PVT-FPC) and operating without helical heat exchanger; and (B) active double slope solar still coupled with series connected partially covered N-PVT-FPC and operating with helical heat exchanger has been developed. Analysis has been executed for 0.25% concentration of CuO, Al_2O_3, TiO_2-metallic nanoparticles; four number of collectors; 100 kg basin fluid (BF/NF) mass and 0.03 kg/s mass flow rate. The maximum values of instantaneous gain thermal energy efficiency (CuO 80.18%; Al_2O_3 71.67%; TiO_2 74.92%) and instantaneous loss thermal energy efficiency (CuO 64.12%; Al_2O_3 59.11%; TiO_2 64.77%) of the system (A) are found to be significantly higher in comparison the basefluid (gain 66.81%; loss 52.42%). The productivity of system (A) and system (B) are (CuO 32%; Al_2O_3 19.23%; TiO_2 6.47%) and (CuO 31.49%; Al_2O_3 26.4%; TiO_2 7.26%) respectively, higher in comparison to the case using basefluid (water). Moreover, thermal energy and exergy; and thermal exergy efficiency has been evaluated for both the systems.

1. Introduction

Potable water is essential for survival of all the creatures on the planet Earth. Moreover, the most important uses of water are in three sectors, viz. (i) domestic, (ii) agriculture and (iii) industrial. Various factors viz. climate change, deforestation, limits to water supply, uneven distribution of water resources, population and pollution; and becoming scare with time which leads to severe water crisis in many parts of the world. Many active organizations like United Nations Development Programme (UNDP), World Health Organization (WHO) and the World Bank (WB) putt efforts to promote the promising projects and policies with time to full-fill the requirement of potable water.

Nowadays, advances in science and engineering developed various high and medium techniques (non-conventional methods) to disinfect the contaminated water to produce the potable water. Whereas, solar distillation (passive/active) is the most prominent, environment friendly and economically viable technology can be used for potable water production [1,2]. In literature, various designs of passive solar stills have been reported in order to improve the performance of the passive stills [3–13].

In active solar stills, external thermal energy (hot water) has been fed into the integrated still. For this purpose, force mode of operation is achieved by using mechanical pump which can be run by non-conventional source of energy such as solar thermal technology or photovoltaic (PV) technology. It makes the active solar stills entirely dependent on renewable energy. External thermal energy from circulated fluid can be transferred to the integrated solar still either directly or via heat exchangers. Coiled tubes are effective heat exchanger as compared to straight tube heat exchangers because of their excellent heat transfer performance, compact size and the enhanced turbulence. Helically coiled heat exchangers (large heat transfer area per unit volume) are frequently used and mostly preferred over the straight tubes due to their excellent heat transfer performance, compact size and enhanced turbulence which intern enhances the heat transfer coefficient of the tube's internal surface.

Soliman [14] suggested the concept (high temperature solar distillation) of feeding external thermal energy into the basin of the still from the solar collector. Later, Rai and Tiwari [15] studied the single basin solar still coupled with flat plate collector and

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Nomenclature

A_m area of the PV module, (m^2)
A_c area of the glazing, (m^2)
A_{gE} surface area of condensing cover of east side of solar still, (m^2)
A_{gW} surface area of condensing cover of west side of solar still, (m^2)
A_B basin area of solar still, (m^2)
C_p specific heat of nanoparticle, (J/kg K)
C_{nf} specific heat of nanofluid, (J/kg K)
C_{bf} specific heat of basefluid, (J/kg K)
D_i diameter of the FPC tube (mm)
d_p diameter of nanoparticle (nm)
F' collector efficiency factor
$h_{1g,E}$ total external heat transfer coefficient on east side, ($W/m^2\ ^\circ C$)
$h_{1g,W}$ total external heat transfer coefficient on west side, ($W/m^2\ ^\circ C$)
$h_{1f,E}$ total internal heat transfer coefficient on east side, ($W/m^2\ ^\circ C$)
$h_{1f,W}$ total internal heat transfer coefficient on west side, ($W/m^2\ ^\circ C$)
h_{EW} internal radiative heat transfer coefficient between glass covers, ($W/m^2\ ^\circ C$)
$h_{ef,E}$ evaporative heat transfer coefficient on east side, ($W/m^2\ ^\circ C$)
L_g thickness of condensing cover, (m)
L_b thickness of basin, (m)
L_p thickness of the absorption plate (m)
M_f mass of fluid in the basin of solar still
$\dot{m}_f$ mass flow rate of the fluid (kg/s)
$\dot{M}_{bf}$ yield obtained from the system (kg/h)
P_{gi} partial saturated vapor pressure of the inner glass cover, (N/m^2)
P_f partial saturated vapor pressure of the fluid, (N/m^2)
PF_1 penalty factor due to glass covers of the module
PF_2 penalty factor due to absorption plate below the module
PF_3 penalty factor due to absorption plate for the portion covered by the glazing
r_{11} outer diameter of the heat exchanger tube (mm)
r_{22} inner diameter of the heat exchanger tube (mm)
T_{goE} outer condensing cover temperature of east side solar still, (°C)
T_{goW} outer condensing cover temperature of west side solar still, (°C)
T_{bf} basefluid temperature, (°C)
T_{nf} nanofluid temperature, (°C)
T_{giE} inner condensing cover temperature of east side of solar still, (°C)
$h_{ef,W}$ evaporative heat transfer coefficient on west side, ($W/m^2\ ^\circ C$)
h_{ba} heat transfer coefficient between basin liner and ambient air, ($W/m^2\ ^\circ C$)
h_{FPC} convective heat transfer in the flat plate collector, ($W/m^2\ ^\circ C$)
h_{HE} convective heat transfer in the heat exchanger, ($W/m^2\ ^\circ C$)
$h_{b,f}$ heat transfer coefficient between basin liner and fluid, ($W/m^2\ ^\circ C$)
h_{pf} heat transfer coefficient from blackened plate to ambient, ($W/m^2\ ^\circ C$)
h_i heat transfer coefficient for space between absorption plate and glazing, ($W/m^2\ ^\circ C$)
h_o heat transfer coefficient from top of PV water collector to ambient, ($W/m^2\ ^\circ C$)
I_{SE} solar intensity on east side of the glass cover, (W/m^2)
I_{SW} solar intensity on west side of the glass cover, (W/m^2)
I_{SW} solar intensity on FPC, (W/m^2)
K_p thermal conductivity of the absorption plate (W/m K)
k_p thermal conductivity of nanoparticle, (W/m K)
k_{nf} thermal conductivity of nanofluid, (W/m K)
k_{bf} thermal conductivity of basefluid, (W/m K)
K_g thermal conductivity of condensing cover, (W/m °C)
L length of the helical heat exchanger (*mm*)
T_{nf} fluid temperature, (°C)
T_v vapor temperature, (°C)
T_a ambient temperature, (°C)
T_{giW} inner condensing cover temperature of west side solar still, (°C)
ΔT_{DSSS} temperature difference between NF and BF in DSSS, (°C)
ΔT_{FPC} temperature difference between NF and BF at the outlet of PVT collectors, (°C)
ΔT_{HE} temperature difference between NF and BF in heat exchanger, (°C)
Δt time interval (s)
$U_{tp,a}$ overall heat transfer coefficient from absorption plate to ambient, ($W/m^2\ ^\circ C$)
$U_{L,m}$ overall heat transfer coefficient from module to ambient, ($W/m^2\ ^\circ C$)
$U_{L,c}$ overall heat transfer coefficient from glazing to ambient, ($W/m^2\ ^\circ C$)
$U_{tc,a}$ overall heat transfer coefficient from cell to ambient from the top surface, ($W/m^2\ ^\circ C$)
U_{ga} overall heat transfer coefficient between condensing cover and ambient air, ($W/m^2\ ^\circ C$)
U_{ba} overall heat transfer coefficient between basin liner and ambient air, ($W/m^2\ ^\circ C$)
U_{gaE} overall heat transfer coefficient between outer condensing cover of east side and ambient air, ($W/m^2\ ^\circ C$)
U_{gaW} overall heat transfer coefficient between outer condensing cover of west side and ambient air, ($W/m^2\ ^\circ C$)
$U_{tc,p}$ overall heat transfer coefficient from cell to the absorption plate, ($W/m^2\ ^\circ C$)
X characteristic length of solar still, (m)

Greek letters

α_g fraction of solar energy absorbed by condensing cover
α_B fraction of solar energy absorbed by basin surface
α_f fraction of solar energy absorbed by fluid
α_c fraction of solar energy absorbed by solar cell
τ_g fraction of solar energy transmitted by top glass cover of the PVT-FPC
$\in_g$ emissivity of condensing cover
$\in_{bf}$ emissivity of the fluid
$\in_{eff}$ effective emissivity of fluid
σ Stefen-Boltzman's constant, ($W/m^2\ K^4$)
φ_p volume fraction of nanoparticles (%)
η_c efficiency of the PVT-FPC collector (%)
β packing factor
β_p thermal expansion coefficient of nanoparticle, (K^{-1})
β_{nf} thermal expansion coefficient of nanofluid, (K^{-1})
β_{bf} thermal expansion coefficient of basefluid, (K^{-1})
μ_{bf} dynamic viscosity of basefluid, ($N\ s/m^2$)
μ_{nf} dynamic viscosity of nanofluid, ($N\ s/m^2$)
ρ_p density of nanoparticle, (kg/m^3)
ρ_{nf} density of nanofluid, (kg/m^3)
ρ_{bf} density of basefluid, (kg/m^3)