Characteristic equation of N-PVT-CPC collector integrated solar still using CNTs & CQD-water based Nanofluid

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Semester long Project

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Certificate

The work embodied in this report entitled "**Characteristic equation of N-PVT-CPC collector integrated solar still using CNTs & CQD-water based Nanofluid** ." has been carried out by Aakash Singh ,Rishabh Sagar and Jairam Madugula as a semester-long project for IV semester. We declare that the work and language included in this project report is free from any kind of plagiarism.

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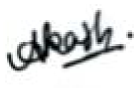

Declaration

This report has been submitted to the Cluster Innovation Centre , University of Delhi towards the requirements of the paper “IV.7 Semester Long Project”.

The details of the work entailed are shared in reference of Prof SWATI ARORA &

Dr. HARENDRA PAL SINGH

Due to privacy concerns, sensitive details have not been shared and other details have been shared with the due and proper consent of the mentors and authorities involved.

Aakash Singh| Madugula Jayaram | Rishabh Sagar

Endorsed by mentors

PROF. SWATI ARORA

DR. HARENDRA PAL SINGH

Abstract

Characteristic equation of N-PVT-CPC collector integrated solar still using CNTs & CQD-water based Nanofluid

This report presents a mathematical model for a solar still system that incorporates N-PVT-CPC collector technology, carbon nanotubes (CNTs), and quantum dot (CQD) water-based nanofluid. The report analyzes the energy and thermal characteristics of the system and derives an equation that describes the relationship between the input parameters and the output performance of the system. Additionally, the report discusses the potential benefits of incorporating CNTs and CQD water-based nanofluid into the system, such as improved thermal conductivity and absorption properties. The conclusion of the report summarizes the findings and suggests potential avenues for future research and development in the field of solar still technology.

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1. Introduction

1.1 Single Slope Solar Still

Solar still replicates the natural hydrological cycle as a closed system. In the still, saline water or feed water placed in a basin with a cover of transparent glass is heated using solar radiation. Condensation takes place at the inner surface of the top cover, and potable water is collected through a channel. Traditional Solar stills are broadly categorised in two major categories i.e., Single Slope Solar Still and Double Slope Solar Still. Given below is a typical Single Slope Solar Still.

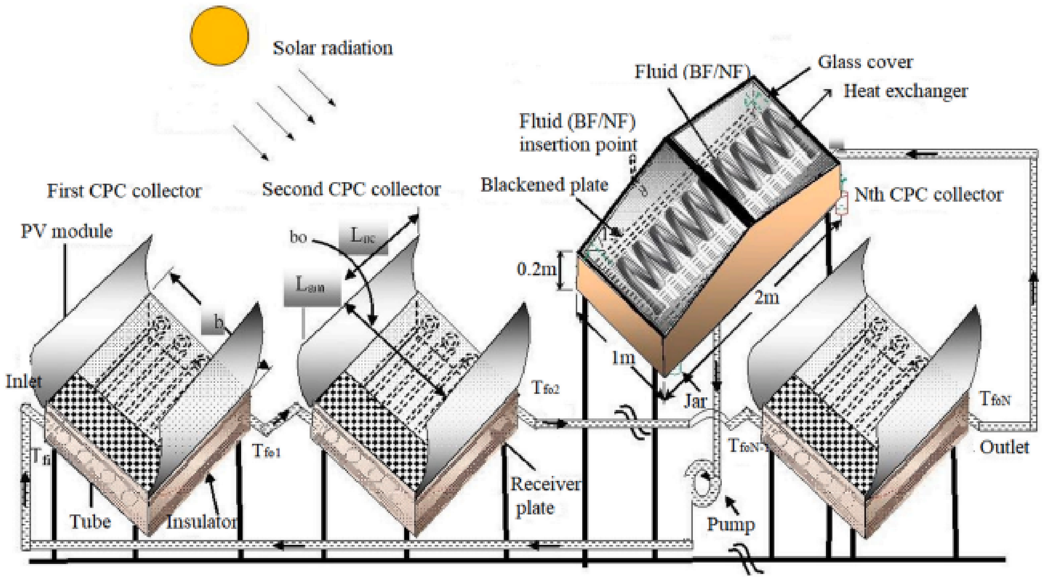

Fig1. Partially covered N- photovoltaic thermal (PVT)-compound parabolic concentrator (CPC) collector integrated double slope solar still (N-PVT-CPC-DSSS) equipped with helically coiled heat exchanger.

1.2 Compound Parabolic concentrator (CPC) Collector

The "CPC" is a combination of both collectors, to collect and concentrate the solar radiations, in diffused form on the cloudy days. These collectors are most commonly used in Japan, Europe and many other countries, having low concentration of solar radiations during winter season. Almost 60% efficiency can be achieved by using these solar collectors. Recently, the energy departments of various countries combined some other technologies with the "CST" power projects. These collectors were basically designed in Germany and these additional technologies only works to provide the value addition. The "CPC" can work upto the temperature of 160°C, and a pressure of six bars; however the optimum results can be obtained at a temperature ranging from 90°C to 100°C. The "CPC" has the ability to increase the temperature of water upto 10°C in cloudy day, when intensity of solar radiation is 1/5th than a regular sunny day.

1.3 System Diagram and Description

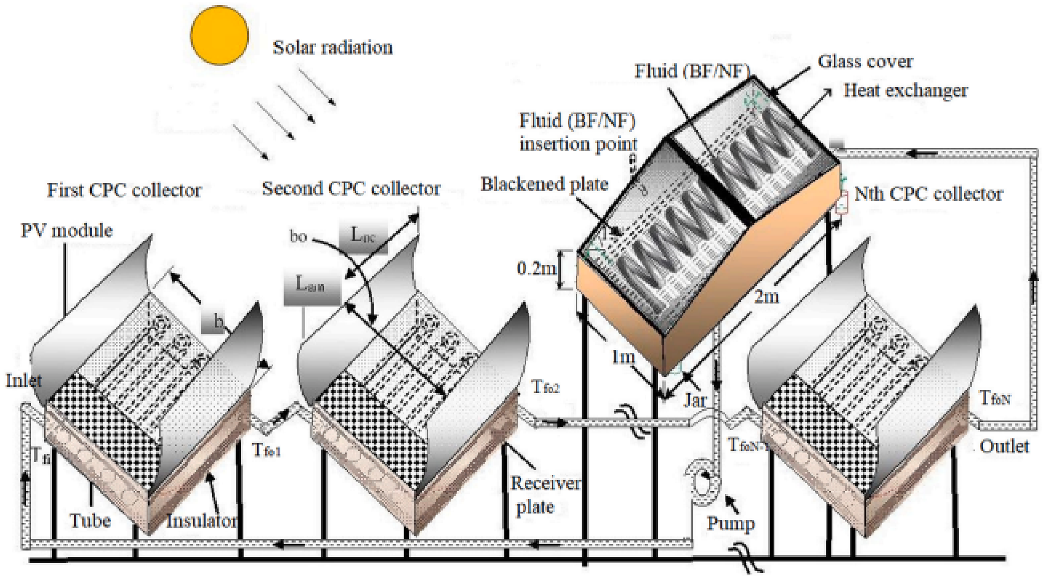

Fig 3: System Diagram of Single Slope Solar Still integrated with CPC

Our system comprises Compound Parabolic concentrator collectors connected in series with single slope solar still integrated with semi transparent PV module and coiled heat exchanger with water based CNT and CQD nanoparticles. Evacuated tube collectors are a way in which heat loss to the environment, inherent in flat-plates, has been reduced. Nanofluids are embryonic fluids and promising thermal-energy carriers in solar thermal applications due to their superior thermo-physical and optical properties. Nanofluids have various features—such as ultrafast heat-transfer capability, lower pumping-power requirement, better stability, superior lubrication, low friction coefficient and erosion, etc.—which efficiently improves system performance. The electricity produced by the semi transparent PV module is used to run the water pump which makes the system completely independent and self sufficient.

1.4 Carbon Nano Tube

Carbon nanotubes (CNTs) are sp^2 nanocarbon materials with tubular structures composed of rolled-up graphene sheets . In addition to unique nanostructures, they exhibit remarkable properties, some derived from the similar properties of graphite and some from their one-dimensional aspects. Depending on their chirality, CNTs can be either semiconductors or metals. In theory, metallic CNTs can carry an electric current density of 4×10^9 A/cm^2, which is more than 1000 times greater than that of metals such as copper. Because of their 1D conductivity, CNTs exhibit ballistic transport along the tube direction, resulting in high intrinsic mobility, exceeding that of many semiconductors. Their mechanical tensile strength is much larger than that of steel, and their thermal conductivity is better than that of diamond.

1.5 Helically coiled heat exchanger

A heat exchanger is a device that is used to transfer thermal energy (enthalpy) between two or more fluids, between a solid surface and a fluid, or between solid particulates and a fluid, at different temperatures and in thermal contact. Helical coil heat exchanger (HCHE) offers distinct advantages, such as improved thermal efficiency, compactness, easy maintenance and lower installed cost. Heat transfer in helical coils has been studied and researched, because of the fluid dynamics inside the pipes of a helical coil heat exchange . Helical coil configuration is very effective for heat exchangers due to their excellent heat transfer performance and compact size as compared to straight tube heat exchangers. The application of curved tubes in laminar flow heat exchange is highly beneficial than straight tubes . Heat transfer rate of helical tube is significantly higher because of the secondary flow caused by the centrifugal force.

1.6 Photovoltaic Thermal Modules

Photovoltaic thermal collectors, typically abbreviated as PVT collectors and also known as hybrid solar collectors, photovoltaic thermal solar collectors are power generation technologies that convert solar radiation into usable thermal and electrical energy. PVT collectors combine photovoltaic solar cells, which convert sunlight into electricity, with a solar thermal collector, which transfers the otherwise unused waste heat from the PV module to a heat transfer fluid.

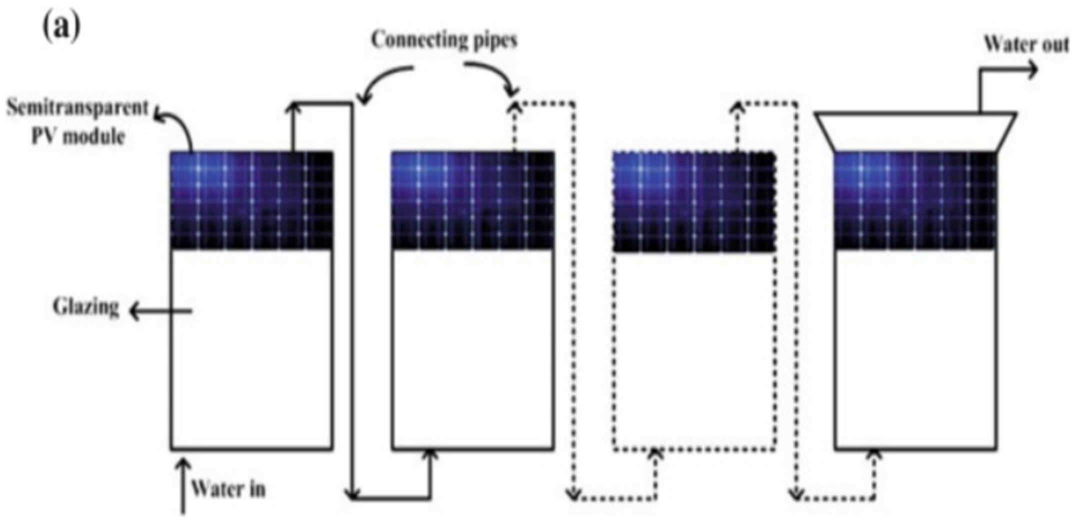

Fig 4: N-Semitransparent PV Modules connected in series

(Source:Advanced Solar Distillation System (GN-Tiwari- Lovdeep Sahota))

THERMAL MODELLING OF A SIMPLE SINGLE SLOPE SOLAR STILL INTEGRATED WITH CPCs AND PV MODULE

Using the diagram below as reference for thermal modelling,

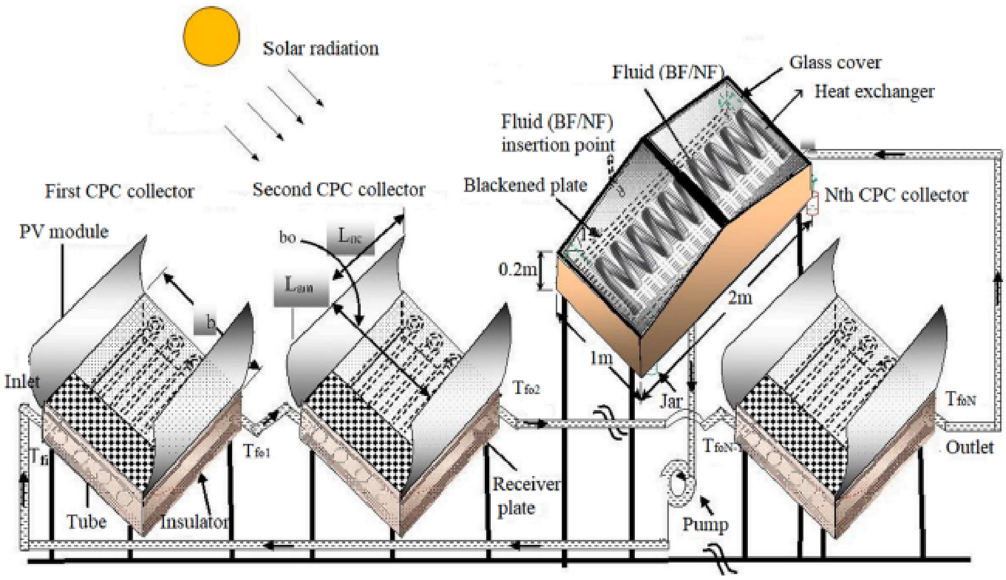

Fig.5: Distillation process in basin type single slope solar distillation system

(Source:Advanced Solar Distillation System (GN-Tiwari- Lovdeep Sahota))

Analysis of system A

(Without heat exchanger)

1. PV MODULE

$$\alpha_c \tau_g \beta_c I(t) A_m = U_{tc,a}(T_c - T_a)A_m + U_{bc,f}(T_c - T_f)A_m + \eta_c \beta_c \tau_g I(t) A_m \quad \text{......................... (1)}$$

2. BASIN LINER

$$(1 - \alpha_f)\alpha_b \tau_g^2 (1 - \beta_c) I(t) A_m = h_{bf}(T_b - T_f)A_b + U_{ba}(T_b - T_a)A_b \quad \text{.................................. (2)}$$

3. PASSIVE CONDENSER

$$\dot{m}_f c_f (T_f - T_{cond}) = U_{tcond,a}(T_{cond} - T_a)A_{cond} + \dot{m}_{cond} L_v \quad \text{.. (3)}$$

4. BASIN FLUID

$$M_f C_f \frac{dT_f}{dt} = h_{bf}\left(T_b - T_f\right)A_b + \alpha_f \tau_g^{\ 2}\left(1 - \beta_c\right)I(t)A_m - h_1\left(T_f - T_m\right)A_m$$

$$- (UA)_{SL}\left(T_f - T_a\right)A_s + \dot{Q}_{UN} - \dot{m}_f c_f\left(T_f - T_{cond}\right) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (4)$$

5. RATE OF THERMAL ENERGY AVAILABLE ($\dot{Q}_{uN}$) AT OUTLET OF *nth PVTCPC*

$$\dot{Q}_{uN} = (\alpha\tau)_{eff} I_b - (UA)_{eff}\left(T_f - T_a\right) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (5)$$

Putting the value of T_b, T_c, T_{cond} in (6), we get

$$M_f C_f \frac{dT_f}{dt} = h_{bf}\left(\frac{\left(1-\alpha_f\right)\alpha_b \tau_g^{\ 2}\left(1-\beta_c\right)I(t)A_m + (h_{bf}T_f + U_{ba}T_a)A_b}{h_{bf}A_b + U_{ba}A_b} - T_f\right)A_b + \alpha_f \tau_g^{\ 2}\left(1 - \beta_c\right)I(t)A_m - h_1$$

$$\left(T_f - \frac{\alpha_c \tau_g \beta_c I(t)A_m - \eta_c \tau_g \beta_c I(t)A_m + (U_{tc,a}T_a + U_{bc,f}T_f)A_m}{(U_{tc,a} + U_{bc,f})A_m}\right)A_m$$

$$- (UA)_{SL}\left(T_f - T_a\right)A_s + \dot{Q}_{uN} - \dot{m}_f c_f\left(T_f - \frac{\dot{m}_f c_f T_f - \dot{m}_{cond}L_v + U_{tcond,a}T_a A_{cond}}{\dot{m}_f c_f + U_{tcond,a}A_{cond}}\right)$$

$$Or$$

$$M_f C_f \frac{dT_f}{dt} + T_f\left(\dot{m}_f c_f + h_{bf}A_b + (UA)_{eff} + (UA)_{SL}A_s + h_1 A_m - \frac{\left(h_{bf}A_b\right)^2}{h_{bf}A_b + U_{ba}A_b} - \frac{(\dot{m}_f c_f)^2}{\dot{m}_f c_f + U_{tcond,a}A_{cond}} - \frac{h_1 U_{bc,f} A_m^{\ 2}}{A_m\left(U_{tc,a} + U_{bc,f}\right)}\right)$$

$$= \left(\left\{\frac{A_b h_{bf}\left(1-\alpha_f\right)\alpha_b \tau_g^{\ 2}\left(1-\beta_c\right)I(t)A_m + h_{bf}U_{ba}T_a A_b^{\ 2}}{\left(A_b h_{bf} + A_b U_{ba}\right)}\right\} + \alpha_f \tau_g^{\ 2}\left(1 - \beta_c\right)I(t)A_m + (UA)_{SL}T_a A_s + (\alpha\tau)_{eff}I_b + (UA)_{eff}T_a + \right.$$

$$\left.\left\{\frac{\dot{m}_f c_f (U_{tcond,a}T_a A_{cond} - \dot{m}_{cond}L_v)}{\dot{m}_f c_f + U_{tcond,a}A_{cond}}\right\} + \left\{h_1 A_m\left(\frac{\alpha_c \tau_g \beta_c I(t)A_m - \eta_c \tau_g \beta_c I(t)A_m + A_m U_{tc,a}T_a}{(U_{tc,a} + U_{bc,f})A_m}\right)\right\}\right)$$

Or

$$\frac{dT_f}{dt} + \mathbf{a}T_f = f(t) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (08)$$

Where,

$$a = \frac{1}{M_f C_f}\left[\dot{m}_f c_f + h_{bf}A_b + (UA)_{eff} + (UA)_{SL}A_s + h_1 A_m - \frac{\left(h_{bf}A_b\right)^2}{h_{bf}A_b + U_{ba}A_b} - \frac{(\dot{m}_f c_f)^2}{\dot{m}_f c_f + U_{tcond,a}A_{cond}} - \frac{h_1 U_{bc,f} A_m^{\ 2}}{A_m\left(U_{tc,a} + U_{bc,f}\right)}\right]$$

Or

$$a = \frac{1}{M_f C_f}\left[\dot{m}_f c_f - \frac{(\dot{m}_f c_f)^2}{\dot{m}_f c_f + U_{tcond,a}A_{cond}} + h_{bf}A_b - \frac{\left(h_{bf}A_b\right)^2}{h_{bf}A_b + U_{ba}A_b} + (UA)_{eff} + (UA)_{SL}A_s + h_1 A_m - \frac{h_1 U_{bc,f} A_m^{\ 2}}{A_m\left(U_{tc,a} + U_{bc,f}\right)}\right]$$

Or

$$a = \frac{1}{M_f C_f}\left[\frac{(\dot{m}_f c_f)^2 + \dot{m}_f c_f U_{tcond,a} A_{cond} - (\dot{m}_f c_f)^2}{\dot{m}_f c_f + U_{tcond,a} A_{cond}} + \frac{(h_{bf} A_b)^2 + h_{bf} U_{ba} A_b^2 - (h_{bf} A_b)^2}{h_{bf} A_b + U_{ba} A_b} + (UA)_{eff} + (UA)_{SL} A_s + \frac{h_1 U_{bc,f} A_m + h_1 U_{tc,a} A_m - h_1 U_{bc,f} A_m}{(U_{tc,a} + U_{bc,f})}\right]$$

Or

$$a = \frac{1}{M_f C_f}\left[\frac{\dot{m}_f c_f U_{tcond,a} A_{cond}}{\dot{m}_f c_f + U_{tcond,a} A_{cond}} + (UA)_{eff} + (UA)_{SL} A_s + \frac{h_{bf} U_{ba} A_b}{h_{bf} + U_{ba}} + \frac{h_1 U_{tc,a} A_m}{(U_{tc,a} + U_{bc,f})}\right]$$

Or

$$a = \frac{1}{M_f C_f}\left[A_1 + A_2 + A_3 + A_4\right]$$

Where

$$A_1 = \frac{\dot{m}_f c_f U_{tcond,a} A_{cond}}{\dot{m}_f c_f + U_{tcond,a} A_{cond}}$$

$$A_2 = (UA)_{eff} + (UA)_{SL} A_s$$

$$A_3 = \frac{h_{bf} U_{ba} A_b}{h_{bf} + U_{ba}}$$

$$A_4 = \frac{h_1 U_{tc,a} A_m}{(U_{tc,a} + U_{bc,f})}$$

$$f(t) = \Bigg[\left[\left\{\frac{A_b h_{bf}(1-\alpha_f)\alpha_b \tau_g^2 (1-\beta_c) I(t) A_m + h_{bf} U_{ba} T_a A_b^2}{(A_b h_{bf} + A_b U_{ba})}\right\} + \alpha_f \tau_g^2 (1-\beta_c) I(t) A_m +\right] (UA)_{SL} T_a A_s + (\alpha\tau)_{eff} I_b + (UA)_{eff} T_a + \left\{\frac{\dot{m}_f c_f (U_{tcond,a} T_a A_{cond} - \dot{m}_{cond} L_v)}{\dot{m}_f c_f + U_{tcond,a} A_{cond}}\right\} + \left\{h_1 A_m \left(\frac{\alpha_c \tau_g \beta_c I(t) A_m - \eta_c \tau_g \beta_c I(t) A_m + A_m U_{tc,a} T_a}{(U_{tc,a} + U_{bc,f}) A_m}\right)\right\}\frac{1}{M_f C_f}$$

Or

$$f(t) = \left[\left\{\frac{h_{bf}\left(1-\alpha_f\right)\alpha_b\tau_g^{\ 2}\left(1-\beta_c\right)I(t)A_m + h_{bf}U_{ba}T_aA_b}{\left(h_{bf}+U_{ba}\right)}\right\} + \ \alpha_f\tau_g^{\ 2}\left(1 - \beta_c\right)I(t)A_m + (UA)_{SL}T_aA_s\right]$$

$$+ (\alpha\tau)_{eff}I_b + (UA)_{eff}T_a + \left\{\frac{\dot{m}_f c_f(U_{tcond,a}T_aA_{cond} - \dot{m}_{cond}L_v)}{\dot{m}_f c_f + U_{tcond,a}A_{cond}}\right\} \quad + \left\{h_1A_m\left(\frac{\alpha_c\tau_g\beta_cI(t) - \eta_c\tau_g\beta_cI(t) + U_{tc,a}T_a}{(U_{tc,a}+U_{bc,f})}\right)\right\}$$

$$\frac{1}{M_fC_f}$$

Or

$$f(t) = \left[\left\{\frac{h_{bf}\left(1-\alpha_f\right)\alpha_b\tau_g^{\ 2}\left(1-\beta_c\right)I(t)A_m + h_{bf}U_{ba}T_aA_b}{\left(h_{bf}+U_{ba}\right)}\right\} + \ \alpha_f\tau_g^{\ 2}\left(1 - \beta_c\right)I(t)A_m + (UA)_{SL}T_aA_s\right]$$

$$+ (\alpha\tau)_{eff}I_b + (UA)_{eff}T_a + \left\{\frac{\dot{m}_f c_f(U_{tcond,a}T_aA_{cond} - \dot{m}_{cond}L_v)}{\dot{m}_f c_f + U_{tcond,a}A_{cond}}\right\} \quad + \left\{h_1A_m\left(\frac{(\alpha_c - \eta_c)\tau_g\beta_cI(t) + U_{tc,a}T_a}{(U_{tc,a}+U_{bc,f})}\right)\right\}\frac{1}{M_fC_f}$$

Or

$$f(t) = \left[F_1 + \ F_2 + F_3 + F_4\right]\frac{1}{M_fC_f}$$

Where

$$F_1 = \left\{\frac{h_{bf}\left(1-\alpha_f\right)\alpha_b\tau_g^{\ 2}\left(1-\beta_c\right)I(t)A_m + h_{bf}U_{ba}T_aA_b}{\left(h_{bf}+U_{ba}\right)}\right\}$$

$$F_2 = \alpha_f\tau_g^{\ 2}\left(1 - \beta_c\right)I(t)A_m + (UA)_{SL}T_aA_s + (\alpha\tau)_{eff}I_b + (UA)_{eff}T_a$$

$$F_3 = \left\{\frac{\dot{m}_f c_f(U_{tcond,a}T_aA_{cond} - \dot{m}_{cond}L_v)}{\dot{m}_f c_f + U_{tcond,a}A_{cond}}\right\}$$

$$F_4 = \left\{h_1A_m\left(\frac{(\alpha_c - \eta_c)\tau_g\beta_cI(t) + U_{tc,a}T_a}{(U_{tc,a}+U_{bc,f})}\right)\right\}$$

By Solving Equation 08, we get

$$T_f = \frac{f(t)}{a}\left[1 - e^{-a\Delta t}\right] + T_{bfo}e^{-a\Delta t} \quad \text{...} (09)$$

Where

$$a = \frac{1}{M_fC_f}\left[A_1 + A_2 + A_3 + A_4\right]$$

$$f(t) = \left[F_1 + \ F_2 + F_3 + F_4\right]\frac{1}{M_fC_f}$$

Thermal Gain

$$n_{g,th} = \frac{h_1(T_f - T_c)}{I(t)} \quad \text{......(10)}$$

Where

$$T_f = \frac{f(t)}{a}\left[1 - e^{-a\Delta t}\right] + T_{bfo}e^{-a\Delta t}$$

$$a = \frac{1}{M_f C_f}[A_1 + A_2 + A_3 + A_4]$$

$$f(t) = \left[F_1 + F_2 + F_3 + F_4\right]\frac{1}{M_f C_f}$$

Thermal Loss

$$n_{L,th} = \frac{\dot{m}_f c_f (T_f - T_{bfo})}{I(t)} \quad \text{......(11)}$$

Where

$$T_f = \frac{f(t)}{a}\left[1 - e^{-a\Delta t}\right] + T_{bfo}e^{-a\Delta t}$$

$$a = \frac{1}{M_f C_f}[A_1 + A_2 + A_3 + A_4]$$

$$f(t) = \left[F_1 + F_2 + F_3 + F_4\right]$$

System B Analysis

(WITH HEAT EXCHANGER)

1. PV MODULE

$$\alpha_c \tau_g \beta_c I(t) A_m = U_{tc,a}\left(T_c - T_a\right)A_m + U_{bc,f}\left(T_c - T_f\right)A_m + \eta_c \beta_c \tau_g I(t) A_m \quad \text{...... (1)}$$

2. BASIN LINER

$$\left(1 - \alpha_f\right)\alpha_b \tau_g^{\ 2}\left(1 - \beta_c\right)I(t)A_m = h_{bf}(T_b - T_f)A_b + U_{ba}(T_b - T_a)A_b \quad \text{...... (2)}$$

3. PASSIVE CONDENSER

$$\dot{m}_f c_f\left(T_f - T_{cond}\right) = U_{tcond,a}\left(T_{cond} - T_a\right)A_{cond} + \dot{m}_{cond} L_v \quad \text{...... (3)}$$

$$T_{cond} = \frac{\dot{m}_f c_f T_f - \dot{m}_{cond} L_v + U_{tcond,a} T_a A_{cond}}{\dot{m}_f c_f + U_{tcond,a} A_{cond}} \quad \text{...... (4)}$$

4. BASIN FLUID

$$M_f C_f \frac{dT_f}{dt} = h_{bf}\left(T_b - T_f\right)A_b + \alpha_f \tau_g^{\,2}\left(1 - \beta_c\right)I(t)A_m - h_1\left(T_f - T_m\right)A_m$$
$$- (UA)_{SL}\left(T_f - T_a\right)A_s + \dot{Q}_{UN} - \dot{m}_f c_f\left(T_f - T_{cond}\right) \ldots\ldots\ldots\ldots (5)$$

5. RATE OF THERMAL ENERGY AVAILABLE ($\dot{Q}_{uN}$) AT OUTLET OF nth PVT CPC

$$\dot{Q}_{uN} = \dot{m}_f c_f\left(T_{FoN} - T_{Fi}\right) \ldots\ldots\ldots\ldots (6)$$

Substituting $T_{FoN} = \frac{I_b\left(AF_R(\alpha\tau)\right)_1 (1-K_K^N)}{\dot{m}_f c_f(1-K_K)} + \frac{T_a(AF_R U_L)_1 (1-K_K^N)}{\dot{m}_f c_f(1-K_K)} + T_{Fi}K_K^N$

$$\dot{Q}_{UN} = \left\{\left(1 - \frac{1-e^{-z}}{1-e^{-z}K_K^N}\right)\left[K_K^N\left(1 - \frac{1-e^{-z}}{1-e^{-z}K_K^N}\right) - 1\right]T_f + \left[\left(\frac{\left(AF_R(\alpha\tau)\right)_1\left(1-K_K^N\right)}{\dot{m}_f c_f\left(1-K_K\right)}\right)e^{-z}\left(\left(e^{-z} - 1\right) + K_K^N\right)\right]I_b(t) + \lfloor\left(\frac{(AF_R U_L)_1 (1-K_K^N)}{\dot{m}_f c_f\left(1-K_K\right)}\right)e^{-z}\left(\left(e^{-z} - 1\right) + K_K^N\right)\rfloor T_a\right\}$$

Or

$$\dot{Q}_{uN} = G_1 T_f + G_2 I_b(t) + G_3 T_a$$

Where

$$G_1 = \dot{m}_f c_f\left(1 - \frac{1-e^{-z}}{1-e^{-z}K_K^N}\right)\left[K_K^N\left(1 - \frac{1-e^{-z}}{1-e^{-z}K_K^N}\right) - 1\right]$$

$$G_2 = \dot{m}_f c_f\left[\left(\frac{\left(AF_R(\alpha\tau)\right)_1 (1-K_K^N)}{\dot{m}_f c_f(1-K_K)}\right)e^{-z}\left(\left(e^{-z} - 1\right) + K_K^N\right)\right]$$

$$G_3 = \dot{m}_f c_f\lfloor\left(\frac{(AF_R U_L)_1 (1-K_K^N)}{\dot{m}_f c_f(1-K_K)}\right)e^{-z}\left(\left(e^{-z} - 1\right) + K_K^N\right)\rfloor$$

Putting the value of T_b, T_c, T_{cond} in (7) we get

$$M_f C_f \frac{dT_f}{dt} = h_{bf}\left(\frac{\left(1-\alpha_f\right)\alpha_b\tau_g^{\,2}\left(1-\beta_c\right)I(t)A_m + (h_{bf}T_f + U_{ba}T_a)A_b}{h_{bf}A_b + U_{ba}A_b} - T_f\right)A_b + \alpha_f\tau_g^{\,2}\left(1 - \beta_c\right)I(t)A_m -$$
$$h_1\left(T_f - \frac{\alpha_c\tau_g\beta_c I(t)A_m - \eta_c\tau_g\beta_c I(t)A_m + (U_{tc,a}T_a + U_{bc,f}T_f)A_m}{(U_{tc,a} + U_{bc,f})A_m}\right)A_m$$
$$- (UA)_{SL}\left(T_f - T_a\right)A_s + \dot{Q}_{uN} - \dot{m}_f c_f\left(T_f - \frac{\dot{m}_f c_f T_f - \dot{m}_{cond}L_v + U_{tcond,a}T_a A_{cond}}{\dot{m}_f c_f + U_{tcond,a}A_{cond}}\right)$$

Or

$$M_f C_f \frac{dT_f}{dt} + T_f\left(\dot{m}_f c_f + h_{bf}A_b - G1 + (UA)_{SL}A_s + h_1 A_m - \frac{\left(h_{bf}A_b\right)^2}{h_{bf}A_b + U_{ba}A_b} - \frac{\left(\dot{m}_f c_f\right)^2}{\dot{m}_f c_f + U_{tcond,a}A_{cond}} - \frac{h_1 U_{bc,f} A_m^{\,2}}{A_m\left(U_{tc,a} + U_{bc,f}\right)}\right) =$$

$$\left(\left\{\frac{A_b h_{bf}\left(1-\alpha_f\right)\alpha_b \tau_g^{\ 2}\left(1-\beta_c\right) I(t) A_m + h_{bf} U_{ba} T_a A_b^{\ 2}}{\left(A_b h_{bf} + A_b U_{ba}\right)}\right\} + \ \alpha_f \tau_g^{\ 2}\left(1 - \beta_c\right) I(t) A_m + (UA)_{SL} T_a A_s + \ G_2 I_b(t)\right)$$

Or

$\frac{dT_f}{dt} + \ aT_f = f(t)$..(08)

Where,

$$a = \frac{1}{M_f C_f}[\dot{m}_f c_f + h_{bf} A_b - G1 + (UA)_{SL} A_s + h_1 A_m - \frac{\left(h_{bf} A_b\right)^2}{h_{bf} A_b + U_{ba} A_b} - \frac{(\dot{m}_f c_f)^2}{\dot{m}_f c_f + U_{tcond,a} A_{cond}} - \frac{h_1 U_{bc,f} A_m^{\ 2}}{A_m\left(U_{tc,a} + U_{bc,f}\right)}]$$

Or

$$a = \frac{1}{M_f C_f}[\dot{m}_f c_f - \frac{(\dot{m}_f c_f)^2}{\dot{m}_f c_f + U_{tcond,a} A_{cond}} + h_{bf} A_b - \frac{\left(h_{bf} A_b\right)^2}{h_{bf} A_b + U_{ba} A_b} - G1 + (UA)_{SL} A_s + h_1 A_m - \frac{h_1 U_{bc,f} A_m^{\ 2}}{A_m\left(U_{tc,a} + U_{bc,f}\right)}]$$

Or

$$a = \frac{1}{M_f C_f}[\frac{(\dot{m}_f c_f)^2 + \dot{m}_f c_f U_{tcond,a} A_{cond} - (\dot{m}_f c_f)^2}{\dot{m}_f c_f + U_{tcond,a} A_{cond}} + \frac{\left(h_{bf} A_b\right)^2 + h_{bf} U_{ba} A_b^{\ 2} - \left(h_{bf} A_b\right)^2}{h_{bf} A_b + U_{ba} A_b} - G1 + (UA)_{SL} A_s + \frac{h_1 U_{bc,f} A_m + h_1 U_{tc,a} A_m - h_1 U_{bc,f} A_m}{\left(U_{tc,a} + U_{bc,f}\right)}]$$

Or

$$a = \frac{1}{M_f C_f}[\frac{\dot{m}_f c_f U_{tcond,a} A_{cond}}{\dot{m}_f c_f + U_{tcond,a} A_{cond}} - G1 + (UA)_{SL} A_s + \frac{h_{bf} U_{ba} A_b}{h_{bf} + U_{ba}} + \frac{h_1 U_{tc,a} A_m}{\left(U_{tc,a} + U_{bc,f}\right)}]$$

Or

$$a = \frac{1}{M_f C_f}[A_1 + A_2 + A_3 + A_4]$$

Where

$$A_1 = \frac{\dot{m}_f c_f U_{tcond,a} A_{cond}}{\dot{m}_f c_f + U_{tcond,a} A_{cond}}$$

$$A_2 = - G1 + (UA)_{SL} A_s$$

$$A_3 = \frac{h_{bf} U_{ba} A_b}{h_{bf} + U_{ba}}$$

$$A_4 = \frac{h_1 U_{tc,a} A_m}{\left(U_{tc,a} + U_{bc,f}\right)}$$

$$f(t) = \left[\left\{ \frac{A_b h_{bf} \left(1-\alpha_f\right)\alpha_b \tau_g^{\ 2}\left(1-\beta_c\right) I(t) A_m + h_{bf} U_{ba} T_a A_b^{\ 2}}{\left(A_b h_{bf} + A_b U_{ba}\right)} \right\} + \ \alpha_f \tau_g^{\ 2}\left(1 - \beta_c\right) I(t) A_m + (UA)_{SL} T_a A_s + \ G_2 I_b(t) \ + \right.$$

$$\left. G_3 T_a + \left\{ \frac{\dot{m}_f c_f (U_{tcond,a} T_a A_{cond} - \dot{m}_{cond} L_v)}{\dot{m}_f c_f + U_{tcond,a} A_{cond}} \right\} \quad + \left\{ h_1 A_m \left(\frac{\alpha_c \tau_g \beta_c I(t) A_m - \eta_c \tau_g \beta_c I(t) A_m + A_m U_{tc,a} T_a}{(U_{tc,a} + U_{bc,f}) A_m} \right) \right\} \right] \frac{1}{M_f C_f}$$

Or

$$f(t) = \left[\left\{ \frac{h_{bf}\left(1-\alpha_f\right)\alpha_b \tau_g^{\ 2}\left(1-\beta_c\right) I(t) A_m + h_{bf} U_{ba} T_a A_b}{\left(h_{bf} + U_{ba}\right)} \right\} + \ \alpha_f \tau_g^{\ 2}\left(1 - \beta_c\right) I(t) A_m + (UA)_{SL} T_a A_s + \ G_2 I_b(t) \ + G_3 T_a + \right.$$

$$\left. \left\{ \frac{\dot{m}_f c_f (U_{tcond,a} T_a A_{cond} - \dot{m}_{cond} L_v)}{\dot{m}_f c_f + U_{tcond,a} A_{cond}} \right\} \quad + \left\{ h_1 A_m \left(\frac{\alpha_c \tau_g \beta_c I(t) - \eta_c \tau_g \beta_c I(t) + U_{tc,a} T_a}{(U_{tc,a} + U_{bc,f})} \right) \right\} \right] \frac{1}{M_f C_f}$$

Or

$$f(t) = \left[\left\{ \frac{h_{bf}\left(1-\alpha_f\right)\alpha_b \tau_g^{\ 2}\left(1-\beta_c\right) I(t) A_m + h_{bf} U_{ba} T_a A_b}{\left(h_{bf} + U_{ba}\right)} \right\} + \ \alpha_f \tau_g^{\ 2}\left(1 - \beta_c\right) I(t) A_m + (UA)_{SL} T_a A_s + \ G_2 I_b(t) \ + G_3 T_a + \right.$$

$$\left. \left\{ \frac{\dot{m}_f c_f (U_{tcond,a} T_a A_{cond} - \dot{m}_{cond} L_v)}{\dot{m}_f c_f + U_{tcond,a} A_{cond}} \right\} \quad + \left\{ h_1 A_m \left(\frac{(\alpha_c - \eta_c) \tau_g \beta_c I(t) + U_{tc,a} T_a}{(U_{tc,a} + U_{bc,f})} \right) \right\} \right] \frac{1}{M_f C_f}$$

Or

$$f(t) = \left[F_1 + \ F_2 + F_3 + F_4\right] \frac{1}{M_f C_f}$$

Where

$$F_1 = \left\{ \frac{h_{bf}\left(1-\alpha_f\right)\alpha_b \tau_g^{\ 2}\left(1-\beta_c\right) I(t) A_m + h_{bf} U_{ba} T_a A_b}{\left(h_{bf} + U_{ba}\right)} \right\}$$

$$F_2 = \alpha_f \tau_g^{\ 2}\left(1 - \beta_c\right) I(t) A_m + (UA)_{SL} T_a A_s + \ G_2 I_b(t) \ + G_3 T_a$$

$$F_3 = \left\{ \frac{\dot{m}_f c_f (U_{tcond,a} T_a A_{cond} - \dot{m}_{cond} L_v)}{\dot{m}_f c_f + U_{tcond,a} A_{cond}} \right\}$$

$$F_4 = \left\{ h_1 A_m \left(\frac{(\alpha_c - \eta_c) \tau_g \beta_c I(t) + U_{tc,a} T_a}{(U_{tc,a} + U_{bc,f})} \right) \right\}$$

By Solving Equation 09, we get

$$T_f = \frac{f(t)}{a}\left[1 - e^{-a\Delta t}\right] + T_{bfo} e^{-a\Delta t} \quad \ldots\ldots (10)$$

Where

$$a = \frac{1}{M_f C_f}\left[A_1 + A_2 + A_3 + A_4\right]$$

$$f(t) = \left[F_1 + \ F_2 + F_3 + F_4\right] \frac{1}{M_f C_f}$$

Thermal Gain

$$n_{g,th} = \frac{h_1(T_f - T_c)}{I(t)} \quad \text{......(11)}$$

Where

$$T_f = \frac{f(t)}{a}\left[1 - e^{-a\Delta t}\right] + T_{bfo}e^{-a\Delta t}$$

$$a = \frac{1}{M_f C_f}[A_1 + A_2 + A_3 + A_4]$$

$$f(t) = \left[F_1 + F_2 + F_3 + F_4\right]\frac{1}{M_f C_f}$$

Thermal Loss

$$n_{L,th} = \frac{\dot{m}_f c_f (T_f - T_{bfo})}{I(t)} \quad \text{......(12)}$$

Where

$$T_f = \frac{f(t)}{a}\left[1 - e^{-a\Delta t}\right] + T_{bfo}e^{-a\Delta t}$$

$$a = \frac{1}{M_f C_f}[A_1 + A_2 + A_3 + A_4]$$

$$f(t) = \left[F_1 + F_2 + F_3 + F_4\right]$$

RELATION BETWEEN HEAT TRANSFER COEFFICIENTS AND TEMPERATURE OF FLUID

The relation between the heat transfer coefficients with the temperature of fluid and its physical properties is given by the following equations:

PROPERTIES OF WATER WITH TEMPERATURE

(i) Thermal Conductivity

$K_{bf} = 0.565 + (0.00263)T_w - 0.000125T_w^{1.5} - (1.515E{-}6)T_w^{2} - 0.000941T_w^{0.}$ ——————————————(1)

(ii) Viscosity

$\mu_{bf} = 557.82 - 19.408T_w - 0.0107T_w^{2} + 0.00082T_w^{2.5} - (2.303E{-}5)T_w$ —————— ——————————(2)

(iii) Density

$\rho_{bf} = 999.79 + 0.0683T_w + 0.136T_w^{2} - 3.116*(10^{-4})T_w$ ——————————————————(3)

(iv) Specific Heat

$C_{bf} = 4.217 - 0.00561T_w + 0.00129T_w^{1.5} - 0.000115T_w^{2} + (4.149E{-}6)T_w^{2}$ ——————————————(4)

PROPERTIES OF THE NANOFLUID WITH TEMPERATURE

(i) Thermal Conductivity

$K_{NF} = (0.9768 + (4.797)(10)^{-5}T^{2} + 0.03823^{*} \phi + 0.004406(T)(\phi))K$ ——————————————(5)

(ii) Viscosity

$\mu_{nf} = (1.871 - 0.050777(T_w) + 0.06839(\phi)^3 + 0.004406(T_w)^2 + (-3.16*10^{-8})T^4)\mu_{bf}$ ————————(6)

(iii) Density

$\rho_{nf} = (1.199 - 0.005633e^{-0.0947T\phi} + (-0.1928)e^{-0.0947T\phi})\rho_{bf}$ ——————————————————————(7)

(iv)Specific heat

$C_{nf} = [(\Psi^{*} \rho_p {}^{*}C_p) + (1-\Psi) (\rho_p {}^{*}C_p)] / \rho_{nf}$ ——————————————————————————(8)

Results and Discussions

The equation derived from the mathematical model describes the performance of the solar still system as a function of the input parameters such as solar radiation, ambient temperature, and the properties of the CNT and CQD-water based nanofluid. The model predicts that the efficiency and output of the solar still system can be significantly improved by incorporating N-PVT-CPC collectors, CNTs, and CQD-water based nanofluid. With the help of the Matlab Software, we solve the above equations, and plot the output of the results, we can see the variations of the physical properties of water with temperature. The plot of variation of Ambient Temperature with time in 24 hrs is given below with maximum temp 40.8°C:

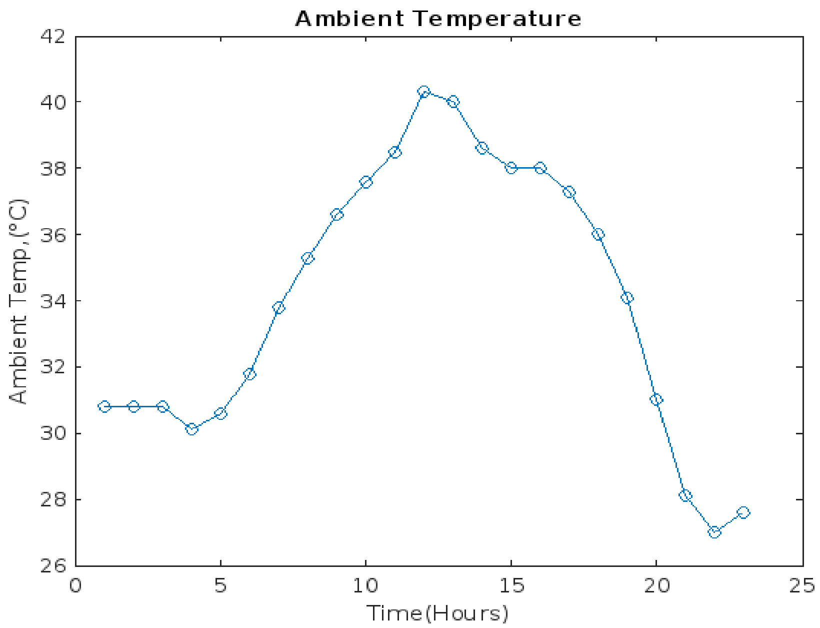

Fig.1

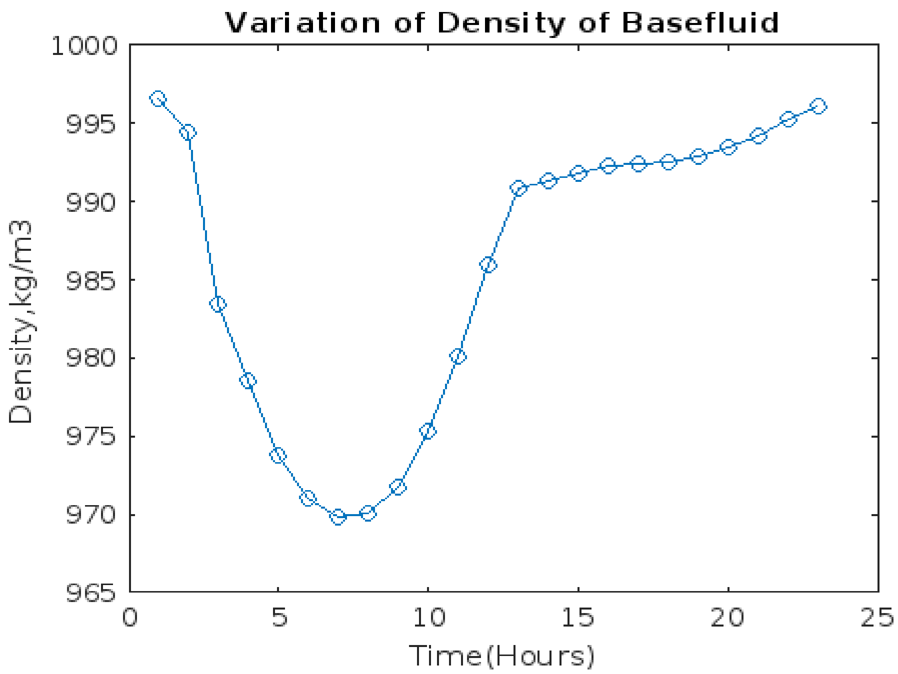

Fig.2

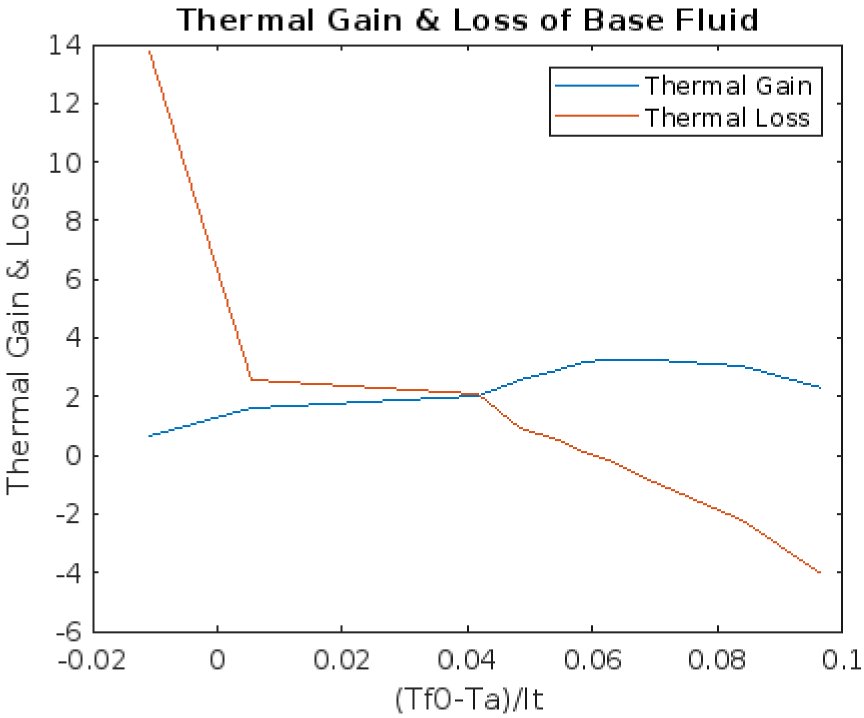

Fig.3

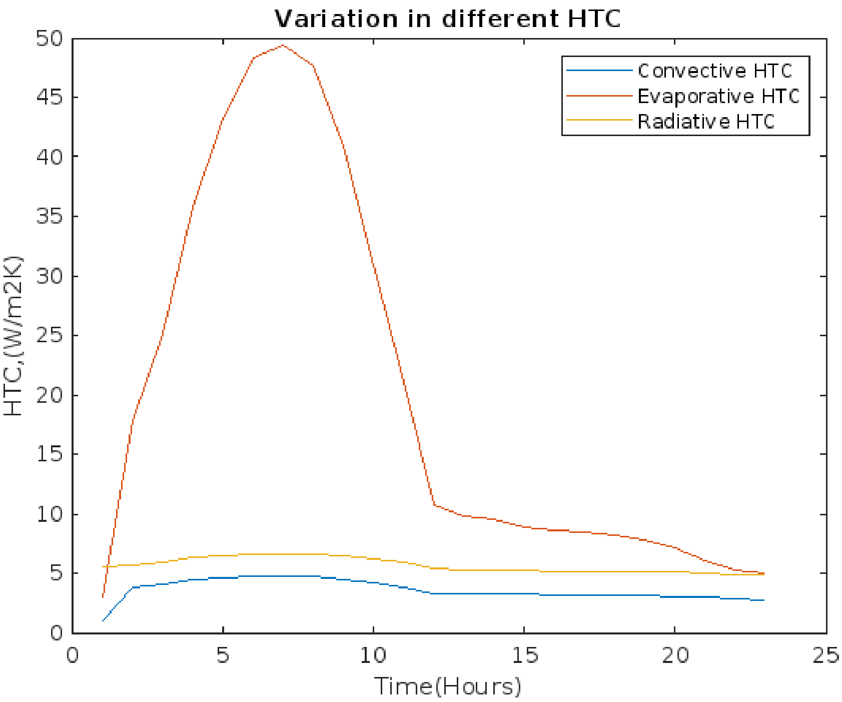

Fig.4

Fig.4 shows different Heat Transfer Coefficient, and the value of evaporative HTC is greater than the other with maximum unit 49 W °C-1 m-2 at the noon.

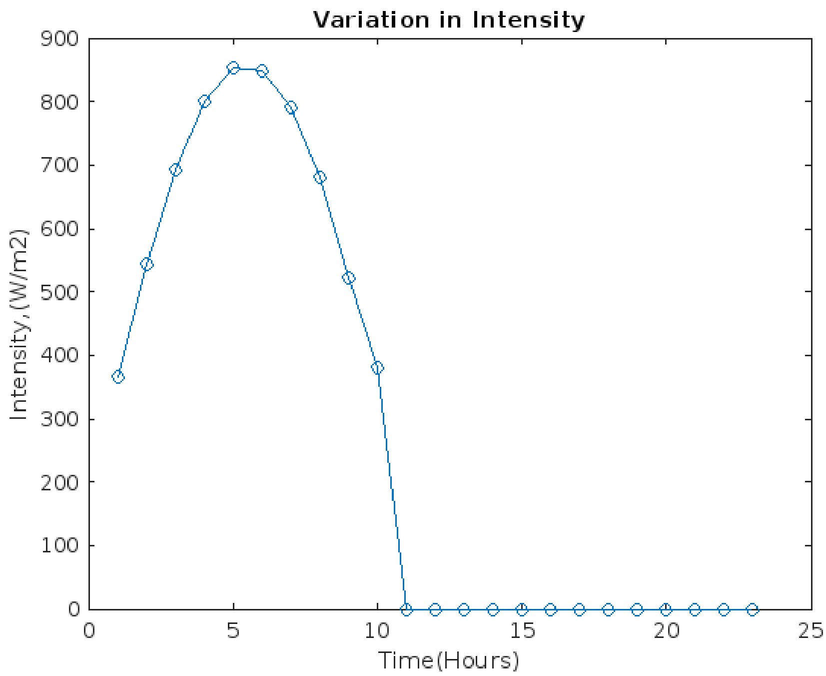

Fig.5

Using the above graph as reference, we can deduce that the intensity is directly dependent Solar Temperature absorbed by our Hybrid Solar Still Since the solar Temperature is at its peak at noon the intensity here also achieves its maxima at noon itself and declines to zero during night-time.

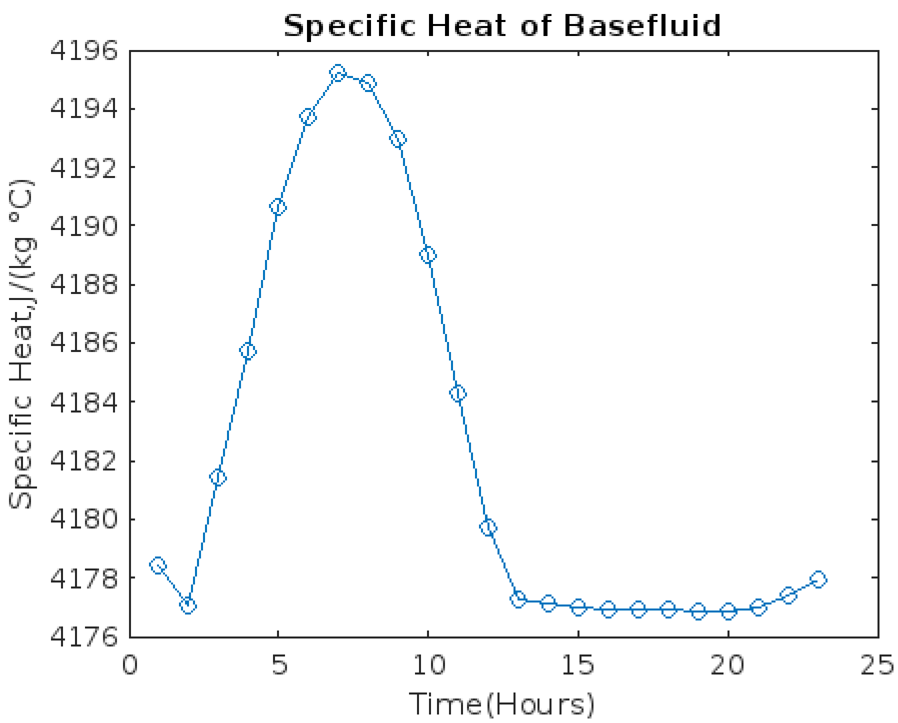
Specific Heat of Basefluid
4196
4194
4192
4190
4188
4186
4184
4182
4180
4178
4176
Specific Heat,J/(kg °C)
0
5
10
15
20
25
Time(Hours)

Fig.6

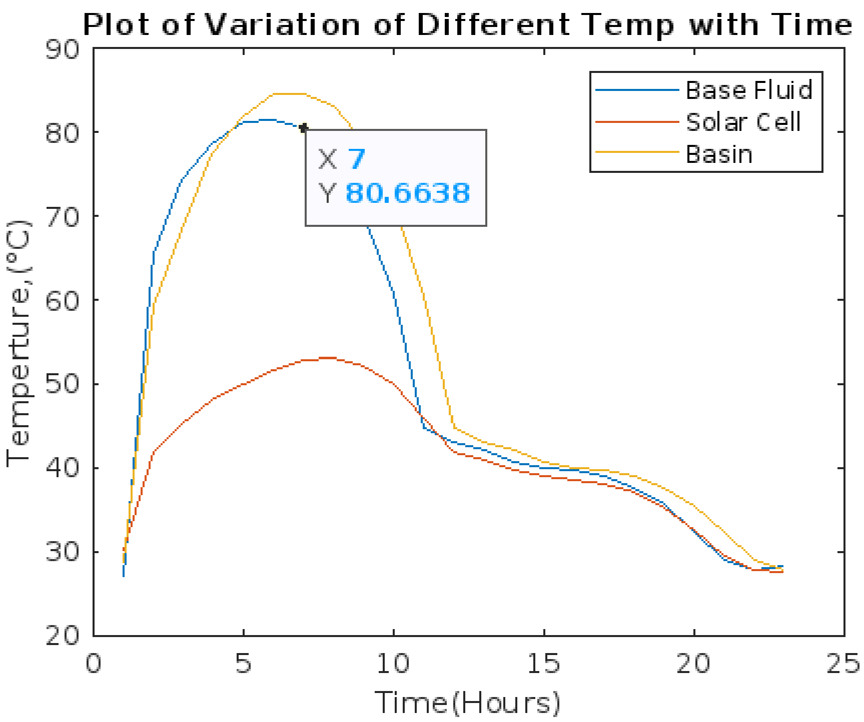
Plot of Variation of Different Temp with Time
90
80
70
60
50
40
30
20
Temperture,(°C)
Base Fluid
Solar Cell
Basin
X 7
Y 80.6638
0
5
10
15
20
25
Time(Hours)

Fig.7

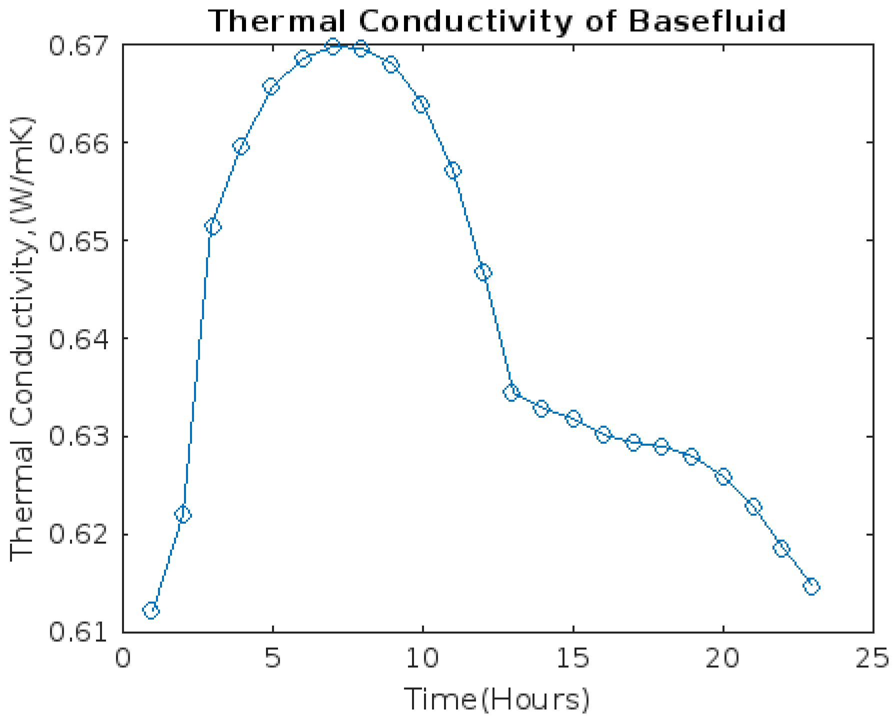
Thermal Conductivity of Basefluid
Thermal Conductivity,(W/mK)
0.67
0.66
0.65
0.64
0.63
0.62
0.61
0
5
10
15
20
25
Time(Hours)

Fig.8

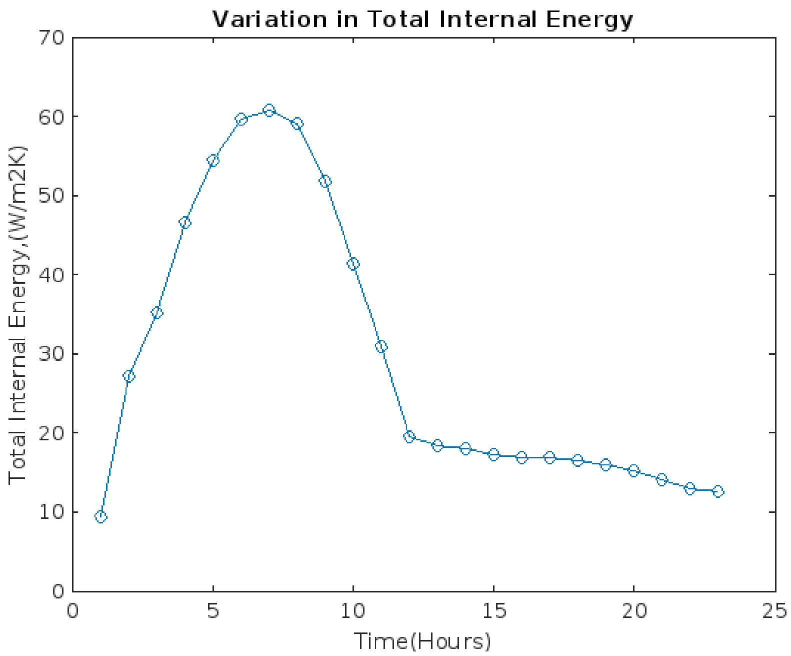
Variation in Total Internal Energy
Total Internal Energy,(W/m2K)
70
60
50
40
30
20
10
0
0
5
10
15
20
25
Time(Hours)

Fig.9

The results of the study suggest that the incorporation of N-PVT-CPC collectors, CNTs, and CQD-water based nanofluid can improve the efficiency and performance of solar stills, making them more viable for use in regions with limited access to clean water. The study also highlights the potential for further research and development in the field of solar still technology, particularly in the area of advanced materials and technologies.

Methodology

The analysis has been carried out for the climatic conditions of India (northern hemisphere) and the climatic data (solar radiation and ambient temperature) of a clear sky day has been obtained from the India Meteorological Department (IMD), Pune, India. The hourly solar intensity at 300 inclination of the PV module (facing due south) has been evaluated using Liu and Jordan formulae. Numerical constants and specification of different components of the proposed systems.

Following equations obtained in next section, the methodology has been executed in MATLAB 2021b in order to study the daily performance of passive single slope solar still integrated with semi-transparent PV module and passive condenser for different packing factors of the solar cell.

(a) Different heat transfer coefficients (HTCs) of the system have been calculated using design parameters using thermo-physical properties of water.

(b) From the estimated HTCs, hourly temperature of solar cell, blackened surface, passive condenser, and basin water; and solar cell efficiency) and module efficiency of the system has been obtained.

(c) Hourly productivity (yield) the proposed system has been calculated.

(d) Electrical energy, net electrical gain, thermal gain, overall thermal energy gain; thermal energy efficiency and overall thermal energy efficiency of the system has been evaluated.

Conclusion

The mathematical model presented in this report provides insights into the performance of a solar still system that incorporates N-PVT-CPC collectors, CNTs, and CQD-water based nanofluid. The model predicts that the efficiency and output of the solar still system can be significantly improved by incorporating these advanced materials and technologies.

The study highlights the potential of these advanced materials and technologies to improve the efficiency and performance of solar stills, making them more viable for use in regions with limited access to clean water. Further research and development in the field of solar still technology, particularly in the area of advanced materials and technologies, could lead to more efficient and cost-effective systems that can help alleviate the global water crisis.

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APPENDIX

1. $\left(AF_R(\alpha\tau)\right)_1 = \left[A_C F_{RC}(\alpha\tau)_{C,eff} + PF_2(\alpha\tau)_{m,eff} + A_M F_{RM}\left(1 - \frac{A_C F_{RC} U_{L,C}}{\dot{m}_f c_f}\right)\right]$
2. $(\alpha\tau)_{c,eff} = PF_C \alpha_p \tau_g \left(\frac{A_{rc}}{A_{ac}}\right)$
3. $(\alpha\tau)_{m,eff} = \left[(\alpha\tau)_{2,eff} + PF_1(\alpha\tau)_{1,eff}\right]$
4. $(\alpha\tau)_{2,eff} = \alpha_p \tau_g^{\ 2}(1 - \beta)\left(\frac{A_{am}}{A_{rm}}\right)$
5. $(\alpha\tau)_{1,eff} = \tau_g \beta_c (\alpha_c - \eta_c)\left(\frac{A_{am}}{A_{rm}}\right)$
6. $A_C F_{RC} = \frac{\dot{m}_f c_f}{U_{L,C}}\{1 - \exp exp\left(-\frac{F' U_{L,C} A_C}{\dot{m}_f c_f}\right)\}$
7. $A_M F_{RM} = \frac{\dot{m}_f c_f}{U_{L,M}}\{1 - \exp exp\left(-\frac{F' U_{L,M} A_m}{\dot{m}_f c_f}\right)\}$
8. $PF_C = \left(\frac{h_{p,f}}{F' h_{p,f} + U_{tp,a}}\right)$
9. $PF_1 = \left(\frac{U_{tc,p}}{U_{tc,p} + U_{tc,a}}\right)$
10. $PF_2 = \left(\frac{h_{p,f}}{F' h_{p,f} + U_{L2}}\right)$
11. $\left(AF_R U_L\right)_1 = A_C F_{RC} U_{L,C} + A_M F_{RM} U_{L,M}\left(1 - \frac{A_C F_{RC} U_{L,C}}{\dot{m}_f c_f}\right)$
12. $U_{tc,a} = \left[\frac{1}{h_0} + \frac{L_g}{K_g}\right]^{-1}$
13. $U_{tc,p} = \left[\frac{1}{h_i} + \frac{L_g}{K_g}\right]^{-1}$
14. $U_{tp,a} = \left[\frac{1}{U_{tc,a}} + \frac{1}{U_{tc,p}}\right]^{-1} + \left[\frac{1}{h'_i} + \frac{1}{h_{pf}} + \frac{L_i}{K_i}\right]^{-1}$
15. $U_{L1} = \left(\frac{U_{tc,a} U_{tc,p}}{U_{tc,a} + U_{tc,p}}\right)$
16. $U_{L2} = U_{L1} + U_{tp,a}$
17. $U_{L,M} = \left(\frac{U_{L2} h_{pf}}{U_{L2} + F' h_{p,f}}\right)$
18. $U_{L,C} = \left(\frac{U_{tp,a} h_{pf}}{U_{tp,a} + F' h_{p,f}}\right)$
19. $h_0 = 5.7 + 3.8v$
20. $h_i = 2.8 + 3v$
21. $z = \frac{2\pi r_{11} UL}{\dot{m}_f c_f}$

S.NO.	NOMENCLATURE	
1.	α_c	Fraction of solar energy absorbed by solar cell
2.	τ_g	Fraction of solar energy transmitted by top glass
3.	β_c	Packing factor of solar cell
4.	$I(t)$	Total solar intensity on the cover
5.	A_m	Area of the PV Module(M^2
6.	$U_{tc,a}$	Overall Heat transfer coefficients from cell to ambient from the top surface
7.	T_c	Temperature of solar cell
8.	T_a	Ambient Temperature
9.	$U_{bc,f}$	Overall heat Transfer coefficients between solar cell and fluid
10.	T_f	Temperature of fluid
11.	η_c	Efficiency of solar cell
12.	α_b	Fraction of Solar Energy absorbed by basin surface
14.	α_f	Fraction of Solar Energy absorbed by basin fluid
15.	h_{bf}	Heat transfer coefficients between basin and fluid
16.	T_b	Temperature of basin
17.	A_b	Area of Basin
18.	U_{ba}	Overall Heat transfer coefficients between basin to ambient
19.	c_f	Specific Heat of the fluid
20.	$\dot{m}_f$	Mass flow rate of fluid (kg/s)
21.	T_{cond}	Temperature of condenser
22.	$U_{tcond,a}$	Overall Heat transfer coefficients between condenser and air
23.	L_v	Latent heat of vaporization
24.	$\dot{m}_{cond}$	
25.	A_{cond}	Area of condenser

Tables

Table 1
Different parameters used in computation.

Parameter	Numerical value	Parameter	Numerical value
α_g	0.05	A_r	1 m^2
α_b	0.8	A_a	2 m^2
α_{BF}	0.6	A_{rm}	0.25 m^2
α_c	0.9	A_{rc}	0.75 m^2
α_p	0.80	A_{am}	0.5 m^2
β_c	0.89	A_{ac}	1.5 m^2
$\in_g$	0.95	L_p	0.002m
$\in_{bf}$	0.95	K_p	64 $(W/m-K)$
σ	5.67×10^{-8} (W/m^2K^4)	K_i	0.166 $(W/m-K)$
τ_g	0.95	L_i	0.1m
$\dot{m}_f$	0.012 (kg/s)	h_i	5.7 (W/m^2-K)
F_{rc}	0.869 m^2	h_i'	5.8 (W/m^2-K)
F_{rm}	0.811 m^2	h_0	9.5 (W/m^2-K)
FF	0.8	h_{pf}	100 (W/m^2-K)
K_p	6 $(W/m\,^\circ C)$	$U_{tc,\,p}$	5.58 (W/m^2-K)
K_g	0.816 $(W/m\,^\circ C)$	$U_{tc,\,a}$	9.20 (W/m^2-K)
K_B	0.035 $(W/m\,^\circ C)$	$U_{tp,\,a}$	4.74 (W/m^2-K)
K_i	0.166 $(W/m\,^\circ C)$	$U_{L,\,m}$	7.58. (W/m^2-K)
L_i	0.100 $(W/m\,^\circ C)$	$U_{L,\,c}$	4.71 (W/m^2-K)
L_g	0.0035 (m)	U_{L1}	3.47 (W/m^2-K)
L_b	0.005m	PF_1	0.378
L_p	0.002m	PF_2	0.934
β_0	0.0045/K	PF_c	0.955
X	0.33m	N	4
d_p	20nm	l_p	500nm
F'	0.968	η_0	0.15

Double slope solar still

Area of the glass cover (A_{gE} and A_{gE})	$1.025m \times 1.025m$
Basin area (A_b)	$2m \times 1m$
Inclination of the cover (θ)	30^0

Parameter	Numerical value	Parameter	Numerical value
Collectors (tube in plate type)			
		Thickness of insulation	0.1 *m*
Tube material	*Copper tubes*	Weight of the collector	48 *kg*
Tube diameter	0.0125*m*	Collector efficiency factor	0.968
Plate thickness	0.002 *m*	Angle of collectors	45^0
Riser- outer diameter	0.0127 *m*	Thickness of top glass	0.004 *m (Toughened)*
Riser thickness	0.56×10^{-3}	Motor used for water pump	*Dc shunt motor* (18 *V*, 40 *W and* 2800 *rpm*)
Spacing between two risers	0.112 *m*	Effective area of collector under glass	1.34 m^2
Effective area of collector under PV module	0.66 m^2		
PV module (under standard test conditions)			
Size of PV module	$1.25\ m \times 0.55\ m$	Fill factor	0.8
No of solar cells	36	Efficiency of module	12%
		Max power rating P_{max}	40 *W*
Helical heat exchanger (Aluminum)			
Length of the heat exchanger	1.937*m*	Diameter of the coil	0.045*m*
Diameter of the coil tube	0.0125*m*	Number of turns	24

Table 2a
Thermo physical properties of vapor [1].

Quantity	Symbol	Expression
Specific heat	C_v	$999.2 + 0.1434 \times (T_v) + 1.101 \times (T_v^2) - 6.7581 \times 10^{-8} \times (T_v^3)$
Density	ρ_v	$353.44/(T_v + 273.15)$
Thermal conductivity	k_v	$0.0244 + 0.7673 \times 10^{-4} \times (T_v)$
Viscosity	μ_v	$1.718 \times 10^{-5} + 4.620 \times 10^{-8} \times (T_v)$
Latent heat of vaporization of fluid	L	$3.1625 \times 10^6 + [1 - (7.616 \times 10^{-4} \times (T_v))]$; *for* $T_v > 70\ ^\circ C$ $2.4935 \times 10^6[1 - (9.4779 \times 10^{-4} \times (T_v) + 1.3132 \times 10^{-7} \times (T_v^2) - 4.7974 \times 10^{-3} \times (T_v^3))]$; *for* $T_v < 70\ ^\circ C$
Partial vapor pressure at condensing cover and fluid temperature	P_{gi}	$P(gi) = exp\left[25.317 - \left(\frac{5144}{T(gi) + 273}\right)\right]$ $P(fluid) = exp\left[25.317 - \left(\frac{5144}{T(fluid) + 273}\right)\right]$
Thermal expansion coefficient	β_v	$1/(T_v + 273.15)$

Note*: Where, $T_v = \frac{(T_f + T_g)}{2}$.

Table 2b
Thermo-physical properties of basefluid [1].

Quantity	Symbol	Expression
Density	ρ_{bf}	$999.79 + 0.0683 \times T_{bf} - 0.0107 \times T_{bf}^2 + 0.00082 \times T_{bf}^{2.5} - 2.303 \times 10^{-5} \times T_{bf}^3$
Specific heat	C_{bf}	$4.217 - 0.00561 \times T_{bf} + 0.00129 \times T_{bf}^{1.5} - 0.000115 \times T_{bf}^2 + 4.149 \times 10^{-6} \times T_{bf}^{2.5}$
Viscosity	μ_{bf}	$\frac{1}{(557.82 - 19.408 \times T_{bf} + 0.136 \times T_{bf}^2 - 3.116 \times 10^{-4} \times T_{bf}^3)}$
Thermal conductivity	k_{bf}	$0.565 + 0.00263 \times T_{bf} - 0.000125 \times T_{bf}^{1.5} - 1.515 \times 10^{-6} \times T_{bf}^2 - 0.000941 \times T_{bf}^{0.5}$

Table 2c
Thermo-physical properties of CNT-water based nanofluid.

Quantity	Expression
Specific heat [29]	$C_{nf} = \varphi_p c_p + (1 - \varphi_p) c_{bf}$
Density [29]	$\rho_{nf} = \varphi_p \rho_p + (1 - \varphi_p) \rho_{bf}$
Thermal conductivity [30]	$k_{nf} = k_{bf} \left[\dfrac{1 - \varphi_p + 2\varphi_p \left(\frac{k_p}{k_p - k_{bf}} \right) \ln \left(\frac{k_p + k_{bf}}{2k_{bf}} \right)}{1 - \varphi_p + 2\varphi_p \left(\frac{k_{bf}}{k_p - k_{bf}} \right) \ln \left(\frac{k_p + k_{bf}}{2k_{bf}} \right)} \right]$
Viscosity [31]	$\mu_{nf} = \mu_{bf}(1 - \varphi_p)^{-2.5}$
Thermal expansion coefficient [29]	$\beta_{nf} = (1 - \varphi_p)\beta_{bf} + \varphi_p \beta_p$

Table 2d
Thermo-physical properties of basefluid and CNTs.

Physical properties	Base fluid (water)	NPs	
		SWCNT	MWCNT
Density, $\rho_p (kg/m^3)$	997	2600	1600
Specific heat, $C_p (J/kg - K)$	4179	425	796
Thermal conductivity, K $(W/m - K)$	0.613	6600	3000

Table 3
Heat transfer coefficients (HTCs) in CPC, HE, and solar still sections [15].

HTCs	Relations
Natural convective HTC from the still basin to fluid	Nusselt number: $(Nu)_f = \frac{h_{b,f} X}{k} = C (RePr)^n$ [Where, C = 0.54 and n = ¼ horizontal plate facing upward] Reynold number: $(Re)_f = \left(\frac{\rho v X}{\mu} \right)_f$; Prandlt number: $(Pr)_f = \left(\frac{\mu C_p}{k} \right)_f$ Rayleigh number: $(Ra)_f = (RePr)_f = \left[\frac{\rho v X C_p}{k} \right]_f$
Internal HTC from fluid surface to inner surface of the glass cover	*From the Cooper and Dunkle model* *Evaporative HTC;* $h_{ev,f} = (0.016273) h_{c,f} \left[\frac{P_f - P_{gi}}{T_f - T_{gi}} \right]$ Convective HTC: $h_{c,f} = (0.844)(\Delta T)^{1/3}$ where; $P_x = exp \left[25.317 - \left(\frac{5144}{T_x + 273} \right) \right]$; $\Delta T = (T_f - T_{gi}) + \left[\frac{(P_f - P_{gi})(T_f + 273)}{2.689 \times 10^5 - P_f} \right]$ *Radiative HTC* $h_{r,f} = \in_{eff} \sigma [(T_f + 273)^2 + (T_{gi} + 273)^2][T_f + T_{gi} + 546]$ where; $\frac{1}{\in_{eff}} = \frac{1}{\in_w} + \frac{1}{\in_g} - 1$
Within CPC collector	*In case of basefluid (water)* $Nu = 1.75 \left(\frac{\mu_{bf}}{\mu_{bf}^b} \right)^{0.14} [Gz_m + 0.0083 (Gr_m Pr_m)^{0.75}]^{1/3}$ Arithmetic mean Graetz number: $Gz_m = \frac{\dot{m}_r C_{bf}}{K_{bf} L}$; Arithmetic mean Grashof number: $Gr_m = \frac{g D^2 \Delta T}{\mu_{bf}^b}$ where, T = Bulk temprature difference; D = tube diameter; L = length of heated section of the tube. *In case of nanofluid*

	In case of nanofluid $h_{FPC} = (Nu)_{nf}\frac{k_{nf}}{D_i}$; $(Nu)_{nf} = \frac{\left(\frac{f}{8}\right)((Re)_{nf} - 10^3)(Pr)_{nf}}{1 + 12.7\sqrt{\left(\frac{f}{8}\right)}\,((Pr)^{2/3} - 1)}$ for $3 \times 10^3 \le (Re)_{nf} \le 5 \times 10^5$ and $0.55 \le (Pr)_{nf} \le 2 \times 10^3$ $(Re)_{nf} = \frac{4\dot{m}_r}{\pi D_i \mu_{nf}}$; $(Pr)_{nf} = \frac{\mu_{nf} C_{nf}}{k_{nf}}$ $\dot{m}_r$= Mass flow rate in any riser and f= Darcy friction factor. Petukhov correlation for smooth tubes $f = [0.79\ \ln\,(Re)_{nf} - 1.64]^{-2}$ Colebrook correlation for roughness of the $\frac{1}{\sqrt{f}} = -2\ log\left(\frac{\epsilon/_{D_i}}{3.7}\right) + \frac{2.51}{(Re)_{nf}\sqrt{f}}$ for $4 \times 10^3 \le (Re)_{nf} \le 10^5$and $0 < \epsilon/_{D_i} < 0.05$ (relative roughness)
Within heat exchanger (HE)	*In case of basefluid (water)* $(Nu)_{nf} = (2.153 + 0.318(De)^{0.643})Pr^{0.177}$ For $20 < De < 2 \times 10^3$ and $0.7 < Pr < 200$ Deans number: $(De)_{nf} = (Re)_{nf}\sqrt{\frac{d_i}{d_c}}$; Reynold number; $(Re)_{nf} = \frac{4\dot{m}_r}{\pi d_i \mu_{nf}}$ d_c = coil diameter; $d_i = r_{11}$ = Inner tube diameter *In case of nanofluid* $(Nu)_{nf} = 3.67(De)^{0.67}\delta^{0.009}\varphi^{1.004}$ $h_{nf} = \frac{(Nu)_{nf}k_{eff}}{d_i}$