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Energy metrics and efficiency analyses of double slope solar distiller unit augmented with *N* identical parabolic concentrator integrated evacuated tubular collectors: a comparative study

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ABSTRACT

This paper communicates the theoretical analysis of the double slope solar distiller unit augmented with *N* identical parabolic concentrator integrated evacuated tubular collectors (NPCETCDS) on the basis of energy metrics and efficiency for the climatic condition of New Delhi. Four weather conditions have been taken for computation. The input data required for calculation has been taken from the Indian Meteorological Department, Pune, India. The computational program has been written in MATLAB. The calculation has been performed for eight collectors and flow of fluid mass per unit time of 0.012 kg s^{-1}. Results of NPCETCDS have been compared with results obtained for double slope solar distiller unit augmented with *N* identical evacuated tubular collectors (NETCDS) for the same number of collectors, the flow of fluid mass per unit time, basin area, and similar weather conditions. It has been concluded that exergy based energy payback time is lower by 88.50%, exergy based life cycle conversion efficiency is higher by 51.93%, and daily exergy efficiency is higher by 78.01% for NPCETCDS than NETCDS for the same number of collectors, the flow of fluid mass per unit time, basin area, and similar weather condition.

Keywords: Energy metrics; Efficiency; Double slope solar still; Concentrator integrated evacuated tubular collectors

1. Introduction

Freshwater is one of the basic needs for the existence of human beings on the planet earth. There is an acute shortage of freshwater all over the world. So, design analysis and installation of active solar distiller unit is the need of time as the world is facing with the problem of scarcity of freshwater particularly developing and under-developed countries. Active solar distiller unit is one that takes heat from outside by some means such as collectors either directly or indirectly. The active solar distiller unit can overcome the problem of low output of passive solar distiller unit. The concept of basin type active solar distiller unit was introduced by Rai and Tiwari [1]. Since then a lot of advancements have been reported by various researchers around the globe. Work on concentrator type collectors integrated with solar still can be summarized as follows:

- Thermal modeling and development of characteristic equation for photovoltaic thermal integrated compound parabolic concentrator collector (PVTCPC)/N identical PVTCPC [2,3]

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- Energy metrics analysis of NPVTCPC integrated solar still (Singh and Tiwari [4])
- Exergoeconomic, enviroeconomic, and productivity analyses of NPVTCPC integrated solar still [5]
- Performance analysis of NPVTCPC integrated solar still [6]
- Characteristic equation development for fully covered NPVTCPC integrated solar still [7]

Singh et al. [8] and Singh and Tiwari [9] reported the development of analytical characteristic equation for solar desalination unit of basin type coupled with *N* alike ETCs. Dev and Tiwari [10] analyzed single slope solar still coupled with ETCs through heater and concluded that the proposed system produced 48% higher yield as compared to conventional single slope solar desalination unit because of heat addition to the basin through heater. In the case of evacuated tubular collector, the heat loss through convection does not take place, and hence higher amount of heat is added. A detailed review of solar desalination unit integrated with various collectors can be seen in Sathyamurthy et al. [11].

Singh et al. [12] performed thermal modeling of solar desalination unit integrated with evacuated tubes and evaluated the performance parameters under natural circulation mode. They found the exergy efficiency of the proposed system in the range of 0.15%–8%. They also found that the integration of evacuated tubes resulted in higher temperature of water in the basin and hence higher yield. The higher temperature of water in the basin was found due to the absence of convective heat loss. Sampathkumar et al. [13] performed experimental study of evacuated tubes integrated solar desalination unit and concluded that the production of freshwater by proposed system was 129% higher than the passive solar desalination unit of same basin area due to addition of heat by collector to the basin. Further, Kumar et al. [14] performed thermal modeling of evacuated tubes coupled with single slope solar desalination unit under forced mode of operation and revealed that the generation of freshwater per hour was higher for the proposed system as compared to similar system having same basin area and working in natural mode because of increased temperature of water kept in basin due to higher amount of heat addition in the case of forced mode of operation. Mosleh et al. [15] made experimental investigation of a desalination system consisting of parabolic trough collector, evacuated tube, and heat pipe. They concluded that the rate of production was 0.27 kg m^{-2} h when aluminum foils were used for transferring heat to heat pipe from evacuated tube.

Shafii et al. [16] studied the modified solar desalination system consisting of evacuated tubes and reported that the highest production of desalinated water took place when the tube was inclined at latitude of the place and the tube was filled with 80% of brackish water because of higher normal radiation received at this angle. Sharshir et al. [17] investigated hybrid solar desalination unit based on the concept of humidification and dehumidification and consisting of evacuated tubes. They reported the gain output ratio of proposed system as 50%. Bait and Si-Ameur [18] investigated the improvement in performance of conventional double slope solar desalination unit by integrating the conventional double slope solar desalination unit with tubular solar collector taking potable water output as the basis. They reported that the heat loss in tubular solar collector was less than the flat plate collector resulting in higher yield and efficiency for the proposed system. Further, Bait [19] performed the exergy and enviroeconomic analyses for the system proposed by Bait and Si-Ameur [18]. Issa and Chang [20] studied experimentally single slope solar desalination unit coupled with evacuated tubes in series–parallel combination and compared this active solar desalination unit with the passive solar desalination unit for the same basin area. They reported that the freshwater production for active solar desalination unit was 61.11% higher than passive solar desalination unit because of supplying heat by collector to the basin of active solar desalination unit.

Singh and Tiwari [21] made the theoretical study of basin type solar desalination unit by integrating with series connected *N* alike ETCs taking energy, exergy, and cost of distillate as basis under optimized condition. They concluded that the cost of producing freshwater was lowered by 15.19% for double slope active solar desalination unit than the single slope active solar distiller having similar geometry due to higher freshwater production in the case of double slope active solar distiller at 280 kg of water mass in basin. Singh and Al-Helal [22] made theoretical analysis for double slope solar desalination unit integrated with *N* alike evacuated tubular collectors on the basis of energy metrics and concluded that the proposed system presented the best performance taking life cycle conversion efficiency (LCCE) as basis followed by double slope solar desalination unit coupled with photovoltaic thermal (PVT) flat plate collectors and PVT compound parabolic concentrator collectors. Singh [23] reported the comparative study of single slope active solar distiller on the basis of energy metrics. Further, Singh [24] performed the exergoeconomic and enviroeconomic analyses of ETC integrated double slope solar distiller and concluded that double slope solar distiller included with ETC performance better than double slope solar distiller integrated with *N* alike PVTCPCs.

From the present survey of literature, it is observed that the study on augmentation of basin type solar still with *N* identical parabolic surface integrated evacuated tubular collectors has not been performed by any researchers. Recently, Mishra et al. [25] have reported the characteristic equation development and energy metrics analyses for *N* identical parabolic surface integrated with *N* identical evacuated tubular collectors (NPCETCs) for preheating process. However, integration of NPCETCs with solar still has not been done. So, the energy metrics and efficiency analyses of NPCETCs integrated solar still have been carried out in the proposed research study. The system reported by Mishra et al. [25] has NPCETCs in open loop. But, NPCETCs has been integrated with double slope solar still (DS) and they are in closed loop. The objective of the proposed research study can be stated as follows:

- To find annual yield and annual energy for NPCETCDS,
- To perform energy metrics analysis on the basis of energy as well as exergy for NPCETCDS,
- To evaluate hourly as well as daily thermal, exergy, and overall efficiencies for NPCETCDS,

- To compare the result of NPCETCDS with the corresponding result of N identical ETC integrated with DS for the same number of collectors, flow of fluid mass per unit time, basin area, and similar weather conditions.

2. Explanations of proposed system NPCETCDS

The schematic diagram of the proposed double slope solar distiller unit augmented with N identical parabolic concentrator integrated evacuated tubular collectors (NPCETCDS) has been presented in Fig. 1 and its specification is represented by Table 1. The elevated side view of the first PCETC is presented in Fig. 2. If collectors are arranged in parallel, discharge is higher but temperature of fluid at the outlet of collector is low. Contrary to this, if collectors are arranged in series, discharge is low but temperature is high at the outlet of the last collector. In the proposed solar desalination unit, series arrangement has been considered as the prime objective of coupling collector with basin is to enhance temperature of water in the basin.

In series arrangement of collectors, the exit of each collector is linked to the entry of its following collectors. Fluid to entrance of first collector comes from basin through variable discharge pump. Fluid gain heat from solar intensity while flowing through tubes of collector and fluid which is available at higher temperature at the exit of last collector goes to the basin again. Thus, a closed loop is formed. Collectors are tilted at 30° (approximately equal to latitude of place) with horizontal surface with an objective of receiving highest annual solar energy.

The double slope solar desalination unit in this effort has been made up of glass reinforced plastic with the basin area of 2 m^2. The orientation of desalination unit is kept toward east–west with an objective of receiving maximum annual solar energy. The condensing cover surface is tilted by 15° with the horizontal surface and the condensing surface is made up of transparent glass. There are two holes – one at the back wall which is used to supply saline/brackish water to basin and the other hole at underside which may be used for cleaning basin when required to do so. A provision of iron stand is made for supporting the whole unit.

When solar radiation impinges on the outer surface of condensing cover, first of all reflection takes place followed by the absorption and transmission. The transmitted radiation falls on the surface of water in the basin. Again, reflection occurs followed by absorption and transmission. Some part of radiation is retained by water mass and the remaining part of radiation goes to the blackened surface at the bottom of basin where almost all radiation coming to the plane gets absorbed. The temperature of basin liner increases which in turn transfer heat to water in basin. In this way, water gets heat from direct solar radiation as well as indirect heat gain through basin liner and a number of collectors. It results in increasing the temperature of water and a temperature difference is created between the surface of water in basin and inner surface of condensing cover. Due to this temperature difference, evaporation of water occurs and vapor in turn gets condensed at the inner surface of condensing cover which trickles down and gets collected in the tray fixed to the inner surface of lower wall. freshwater from the tray is collected in a jar through pipe.

3. Thermal modeling

Assumptions [26] for writing energy balance equations for different components of NPCETCDS are as follows:

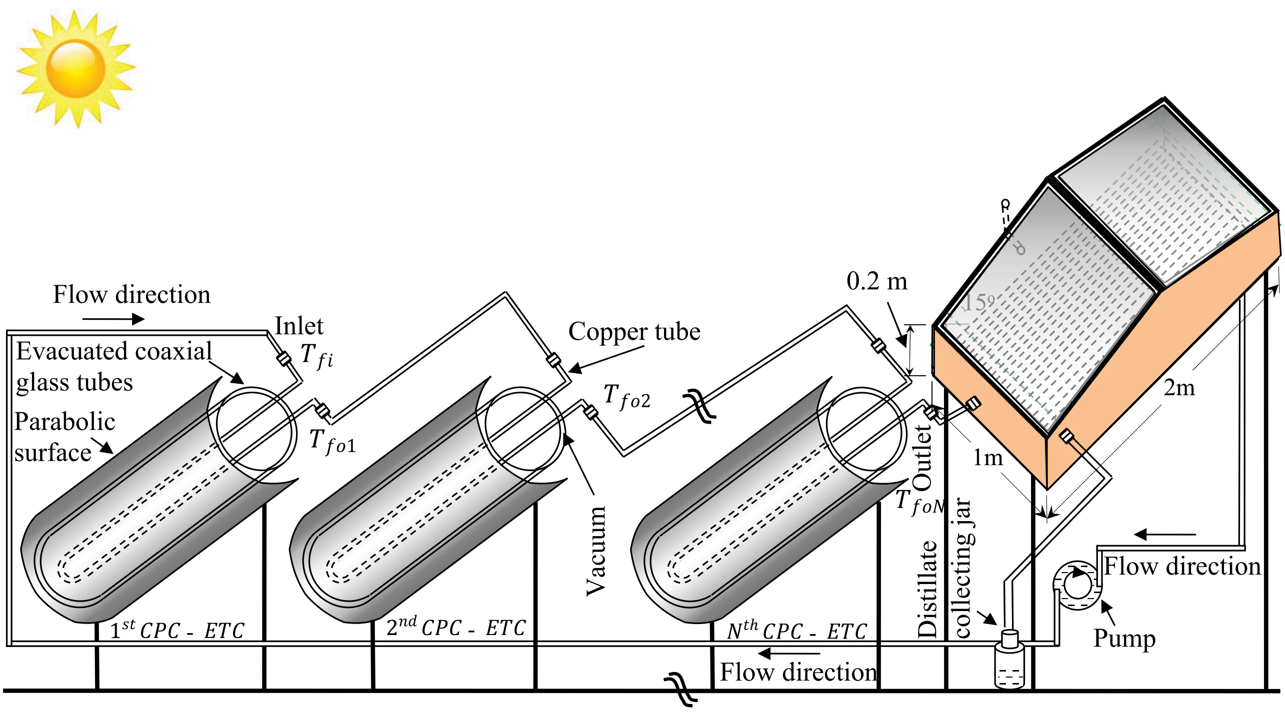


Fig. 1. Schematic diagram of proposed N alike parabolic concentrator collector incorporated with double slope solar still (NPCETCDS).

Table 1
Specifications of double slope solar distiller unit augmented with N identical parabolic concentrator integrated evacuated tubular collectors (NPCETCDS)

Double slope active solar still			
Component	Specification	Component	Specification
Length	2 m	Cover material	Glass
Width	1 m	Orientation	East–west
Inclination of glass cover	15°	Thickness of glass cover	0.004 m
Height of smaller side	0.2 m	K_g	0.816 W m^{-1} K
Material of body	GRP	Thickness of insulation	0.1 m
Material of stand	GI	K_i	0.166 W m^{-1} K
Parabolic concentrator integrated evacuated tubular collectors (PCETC)			
Type and no. of collectors	PCETC, N	α_p	0.8
DC motor rating	12 V, 24 W	F'	0.986
Diameter of inner copper tube	0.0125 m	τ_g	0.95
Thickness of copper tube	0.0005 m	K_g (Wm^{-1} K^{-1})	1.09
Outer radius of outer glass tube of evacuated coaxial glass tube	0.024 m	Angle of PCETC with horizontal	30°
Inner radius of inner glass tube of evacuated coaxial glass tube	0.0165 m	Length of each copper tube	2.0 m
Thickness of outer/inner glass tube of evacuated coaxial glass tube	0.002 m	ρ	0.85
		Aperture area	0.82896 m^2
		Receiver area	0.27632 m^2

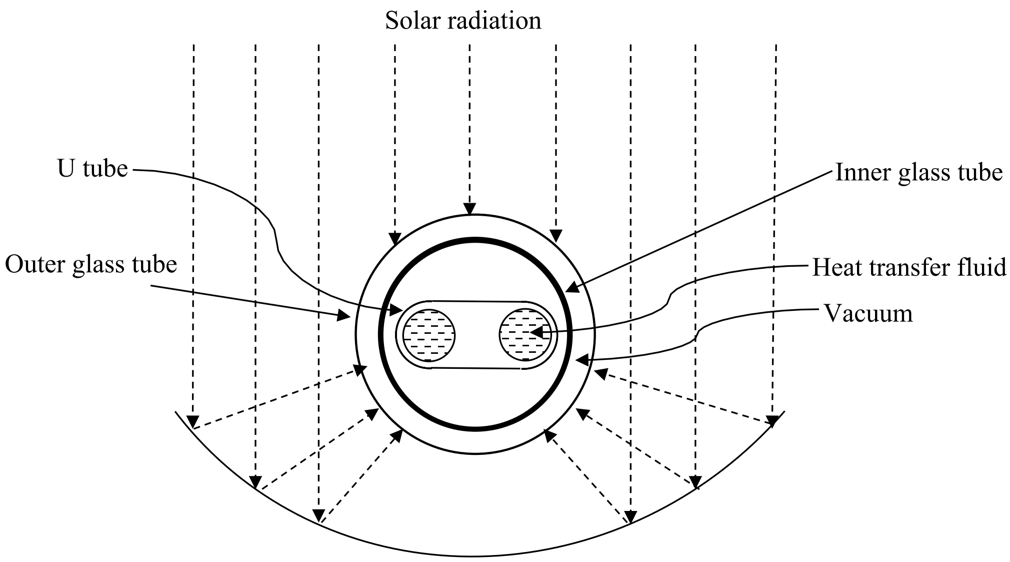


Fig. 2. Elevated view of parabolic concentrator integrated evacuated tubular collector.

- The proposed NPCETCDS is in quasi steady state condition.
- The variation in temperature across the thickness of insulating and glass materials is negligible.
- Condensing covers, absorbing, and insulating materials have negligible small heat capacity.
- Heat flow has been considered as one-dimensional.
- The seepage of vapor through joints in solar distiller unit is negligible.
- The depth of water in solar distiller unit is kept constant [27].
- The formation of layers in water mass kept in the basin does not take place.
- The condensation having film type characteristic takes place at inside plane of condensing cover.

Equations for different components of NPCETCDS on the ground of equating net energy input to net energy output can be written as follows:

3.1. For N alike parabolic concentrator integrated evacuated tubular collector arranged in series

Following Mishra et al. [25], the expression for the temperature at the exit of Nth PCETC and it can be expressed as:

$$T_{\text{foN}} = \frac{\text{PF}_1(\alpha\tau)_{\text{eff}}(A_rF_r)}{\dot{m}_fC_f}\frac{(1-K_K^N)}{(1-K_K)}I_b(t) + \frac{(A_rF_r)U_L}{\dot{m}_fC_f}\frac{(1-K_K^N)}{(1-K_K)}T_a + K_K^N T_{\text{fi}} \tag{1}$$

where N is the number of parabolic concentrator integrated evacuated tubular collector.

The amount of heat gained per unit time from N alike PCETCs can be written as:

$$\dot{Q}_{\text{UN}} = \dot{m}_fC_f(T_{\text{foN}} - T_{\text{fi}}) \tag{2}$$

Putting the expression of T_{foN} from Eqs. (1) into (2) and rearranging, one can get:

$$\dot{Q}_{\text{uN}} = (\text{PF}_1)(\alpha\tau)_{\text{eff}}\frac{(1-K_k^N)}{(1-K_k)}I_b(t) - (A_rF_r)U_L\frac{(1-K_k^N)}{(1-K_k)}(T_{\text{fi}} - T_a) \tag{3}$$

3.2. Solar distiller unit

Equation based on balancing the energy per unit time for outer plane of condensing cover oriented toward east can be expressed as:

$$\frac{K_g}{L_g}(T_{\text{giE}} - T_{\text{goE}})A_{\text{gE}} = h_{1\text{gE}}(T_{\text{goE}} - T_a)A_{\text{gE}} \tag{4}$$

Equation for inside plane of condensing drape oriented toward east on the basis of balancing energy per unit time can be expressed as:

$$\alpha'_g I_{\text{SE}}(t)A_{\text{gE}} + h_{1\text{wE}}(T_w - T_{\text{giE}})\frac{A_b}{2} - h_{\text{EW}}(T_{\text{giE}} - T_{\text{giW}})A_{\text{gE}} = \frac{K_g}{L_g}(T_{\text{giE}} - T_{\text{goE}})A_{\text{gE}} \tag{5}$$

Equation based on balancing the energy per unit time for outer plane of condensing cover oriented toward west can be expressed as:

$$\frac{K_g}{L_g}(T_{\text{giW}} - T_{\text{goW}})A_{\text{gW}} = h_{1\text{gW}}(T_{\text{goW}} - T_a)A_{\text{gW}} \tag{6}$$

Equation for inside plane of condensing cover oriented toward west on the basis of balancing energy per unit time can be expressed as:

$$\alpha'_g I_{\text{SW}}(t)A_{\text{gW}} + h_{1\text{wW}}(T_w - T_{\text{giW}})\frac{A_b}{2} + h_{\text{EW}}(T_{\text{giE}} - T_{\text{giW}})A_{\text{gE}} = \frac{K_g}{L_g}(T_{\text{giW}} - T_{\text{goW}})A_{\text{gW}} \tag{7}$$

Equation for basin liner based on balancing energy can be written as:

$$\alpha'_b(I_{\text{SE}}(t) + I_{\text{SW}}(t))\frac{A_b}{2} = h_{\text{bw}}(T_b - T_w)A_b + h_{\text{ba}}(T_b - T_a)A_b \tag{8}$$

Equation for water mass based on balancing energy can be expressed as:

$$(M_wC_w)\frac{dT_w}{dt} = (I_{\text{SE}}(t) + I_{\text{SW}}(t))\alpha'_w\frac{A_b}{2} + h_{\text{bw}}(T_b - T_w)A_b - h_{1\text{wE}}(T_w - T_{\text{giE}})\frac{A_b}{2} - h_{1\text{wW}}(T_w - T_{\text{giW}})\frac{A_b}{2} + \dot{Q}_{\text{uN}} \tag{9}$$

Using Eqs. (3)–(9), one can find expressions for temperature of water and glass temperatures (T_{giE}, T_{giW}, T_{goE}, T_{goW}) as follows:

$$T_w = \frac{\bar{f}(t)}{a}(1 - e^{-at}) + T_{w0}e^{-at} \tag{10}$$

$$T_{\text{giE}} = \frac{A_1 + A_2T_w}{P} \tag{11}$$

$$T_{\text{giW}} = \frac{B_1 + B_2T_w}{P} \tag{12}$$

Expressions for various unknown terms used in Eqs. (1)–(12) are given in Appendix – A.

In Eqs. (1), (3), and (10)–(12), if $A_a = A_r$; $\rho = 1$; and $I_b(t) = I(t)$, then expressions of T_{foN}, $\dot{Q}_{\text{UN}}$, T_w, T_{giE}, T_{giW} for N alike ETCs integrated with double slope solar distillation system will be obtained.

4. Analysis

Four kinds of climatic conditions of New Delhi for each month of year have been taken for the theoretical investigation of systems NPCETCDS and NETCDS. These four climatic conditions can be defined in terms of number of sunshine hours (N') and ratio (p') of daily diffuse to daily global irradiation. They can be written as follows [28]:

(a) Clear day (blue sky)	$p' \le 0.25$ and $N' \ge 9$ h
(b) Hazy day (fully)	$0.25 \le p' \le 0.50$ and $7\text{ h} \le N' \le 9$ h
(c) Hazy and cloudy (partially)	$0.50 \le p' \le 0.75$ and $5\text{ h} \le N' \le 7$ h
(d) Cloudy day (fully)	$p' \ge 0.75$ and $N' \le 5$ h

4.1. Analysis for production of potable water

The production of potable water on hourly basis can be evaluated for systems NPCETCDS and NETCDS as:

$$\dot{m}_{\text{ew}} = \frac{\left[h_{\text{ewE}}\left(T_w - T_{\text{giE}}\right) + h_{\text{ewW}}\left(T_w - T_{\text{giW}}\right)\right]\left(\frac{A_b}{2}\right)}{L'} \times 3{,}600 \quad (13)$$

The value of daily production of potable water for kind (a) climatic condition can be evaluated by adding hourly production of potable water from Eq. (13) and the same method has been followed to calculate daily production of potable water for the remaining climatic conditions (kinds b–d). The monthly production of potable water for kind (a) climatic condition can be evaluated as the product of production of potable water on daily basis and the corresponding number of days (n'). The same method has been followed to evaluate the monthly production of potable water for the remaining climatic conditions (kinds b–d). By adding production of potable water for kind (a), kind (b), kind (c), and kind (d) climatic conditions give the total production of potable water for each month. The annual production of potable water (yield) can be computed as the summation of monthly production of potable water for 12 month.

4.2. Exergy and energy analyses

First law (energy) and second law (entropy) of thermodynamics can be applied to compute exergy of systems NPCETCDS and NETCDS. The hourly output of exergy $\dot{\text{E}}\text{x}_{\text{out}}$ for NPCETCDS/NETCDS can be expressed as [29]:

$$\dot{E}x_{\text{out}} = \frac{A_b}{2} h_{\text{ewgE}}\left[\left(T_w - T_{\text{giE}}\right) - (T_a + 273) \times \ln\left\{\frac{(T_w + 273)}{\left(T_{\text{giE}} + 273\right)}\right\}\right] + \frac{A_b}{2} h_{\text{ewgW}}\left[\left(T_w - T_{\text{giW}}\right) - (T_a + 273) \times \ln\left\{\frac{(T_w + 273)}{\left(T_{\text{giW}} + 273\right)}\right\}\right] \quad (14)$$

The various unknown terms used in Eq. (14) has been presented in Appendix – A.

The analysis for energy of systems NPCETCDS and NETCDS has been done using first law of thermodynamics. The expression of hourly energy ($\dot{E}_{\text{out}}$) for NPCETCDS/NETCDS can be written as:

$$\dot{E}_{\text{out}} = \frac{\left(\dot{m}_{\text{ew}} \times \text{L}\right)}{3{,}600} \quad (15)$$

The value of daily exergy for kind (a) climatic condition can be evaluated by adding hourly exergy from Eq. (14) and the same method has been followed to calculate daily exergy for the remaining climatic conditions (kinds b–d). The monthly exergy for kind (a) climatic condition can be evaluated as the product of daily exergy and the corresponding number of days (n'). The same method has been followed to evaluate the monthly exergy for the remaining climatic conditions (kinds b–d). By adding exergy for kind (a), kind (b), kind (c), and kind (d) climatic conditions, exergy for each month is obtained. The annual exergy can be computed as the summation of monthly exergy for 12 month. Similarly, annual energy has been computed using Eq. (15).

4.3. Energy metrics analysis on the basis of energy as well as exergy

Energy metrics is the analysis parameter to give us the performance of the technology and help us to judge the technology on the grounds of its uniqueness or its drawbacks, etc. It is a very prudent aspect regarding all the technologies especially the one which is based on renewable energy. The technology is of no use if the amount of energy/exergy generated by that technology during its life-time is less than that of its embodied energy (EBE; energy/exergy which is being used to develop that technology). Energy metrics consist of several analytical parameters like ET (energy payback time), EP (energy production factor), and LCCE. These factors represent nothing but a comparison between energy required for manufacturing the whole set up and energy produced by that set up, which in turn become the determining factor of the technological and economical success of that particular set up [30]. Embodied energy is described as the total (direct or indirect) energy which is consumed for generating an element or set up. As a better economic approach, whether the study is being on theoretical or experimental grounds, the EBE and payback time should be as low as possible. To keep this payback time low: collectors, water pumps, etc are used for enhancing the performance.

4.3.1. Energy payback time

This parameter is mathematically expressed as the ratio of the EBE to annual energy output (E_{annual}) so as to compare both of them with respect to each other. This parameter represents the period of time required by the set up in order to return that much amount of energy which is being consumed to generate that set up (EBE). Mathematically, energy payback time with respect to energy (ET_e) and energy payback time with respect to exergy (ET_{ex}) can be expressed as:

$$\text{ET}_e = \frac{\text{EBE}}{E_{\text{annual}}} \quad (16)$$

$$\text{ET}_{\text{ex}} = \frac{\text{EBE}}{\text{Ex}_{\text{annual}}} \quad (17)$$

4.3.2. Energy production factor

The inclusive performance of a solar distillation system is being represented by the virtue of a energy metrics parameter, that is, EP. Mathematically, EP is nothing but the reciprocal of ET. So, we can conclude that EP is inversely proportional to ET. As we have discussed, a better system has a lower ET. Thus, for a better performance of solar stills on both economic and technological ground the value of EP must be higher. EP on the basis of energy and exergy, respectively, for active solar distillation units can be expressed as:

$$\mathrm{EP}_e = \frac{E_{\text{annual}}}{\mathrm{EBE}} \tag{18}$$

$$\mathrm{EP}_{\text{ex}} = \frac{\mathrm{Ex}_{\text{annual}}}{\mathrm{EBE}} \tag{19}$$

Here, $\mathrm{Ex}_{\text{annual}}$ stands for the exergy output in a year.

4.3.3. Life cycle conversion efficiency

This energy metrics parameter represents how efficient the system is in converting the input of solar energy into the net output energy throughout its lifetime period. Higher the efficiency of the system, higher will be the capability of the system to get maximum output energy from the input energy. Ideal LCCE value of the system should be unity, that is, an ideal system possess the capability to convert the total input energy into output energy. Idea of LCCE parameter was given by Tiwari and Mishra [30]. Mathematically, LCCE on the grounds of energy and exergy respectively can be expressed as:

$$\mathrm{LCCE}_e = \frac{E_{\text{annual}} \times n - (\mathrm{EBE})}{\mathrm{AS} \times n} \tag{20}$$

$$\mathrm{LCCE}_{\text{ex}} = \frac{\left[Ex_{\text{annual}} \times (n)\right] - (\mathrm{EBE})}{\mathrm{AS} \times 0.93 \times n} \tag{21}$$

93% of the total annual solar energy represents annual solar exergy and this concept was given by Petela [31]. Here, n stands for life of the system and AS stands for solar energy in a year.

4.4. Efficiency analysis

The efficiency analysis has been done using the concept of first law and second law of thermodynamics. Thermal efficiency evaluation of the system is based on first law of thermodynamics; whereas, exergy efficiency computation is based on second law of thermodynamics. Entropy concept has been used for the computation of exergy.

4.4.1. Thermal efficiency analysis

Following Tiwari [32], the hourly and daily thermal efficiencies of NPCETCDS/NETCDS can be written as:

$$\eta_{h,\text{th}} = \frac{\dot{m}_{\text{ew}} \times L}{\left[\dot{Q}_{\text{uN}}(t) + A_b \times I_s(t) + \dfrac{\text{hourly pump work}}{0.38}\right] \times 3{,}600} \times 100 \tag{22}$$

$$\eta_{d,\text{th}} = \frac{\sum_{t=1}^{24} \dot{m}_{\text{ew}} \times L}{\sum_{t=1}^{24}\left[\dot{Q}_{\text{uN}}(t) + A_b \times I_s(t) + \left(\dfrac{\text{hourly pump work}}{0.38}\right)\right] \times 3{,}600} \times 100 \tag{23}$$

where $\dot{Q}_{\text{uN}}(t)$ is heat gained on hourly basis from NPCETCs which can be evaluated with the help of Eq. (3). The value of $\dot{m}_{\text{ew}}$ can be calculated with of help of Eq. (13). Here, it should be noted that the value of solar intensities, heat gain, and pump work used in Eqs. (22) and (23) for off sunshine hours are zero. However, yield will continue to appear for off sunshine hours also due to heat content of water mass. The value of latent heat has been taken as 2,400 kJ kg^{-1}.

4.4.2. Exergy efficiency analysis

Following Tiwari [32], the hourly and daily exergy efficiencies for NPCETCDS/NETCDS can be written as:

$$\eta_{h,\text{ex}} = \frac{\dot{\mathrm{E}}\mathrm{x}_{\text{out}}(t)}{\dot{\mathrm{E}}\mathrm{x}_c(\mathrm{t}) + 0.933 \times \left(A_b \times I_s(\mathrm{t})\right) + (\text{hourly pump work})} \times 100 \tag{24}$$

$$\eta_{d,\text{ex}} = \frac{\sum_{t=1}^{24}\left[\dot{\mathrm{E}}\mathrm{x}_{\text{out}}(t)\right]}{\sum_{t=1}^{24}\left[\dot{\mathrm{E}}\mathrm{x}_c(t) + 0.933 \times \left(A_b \times I_S(t)\right) + (\text{hourly pump work})\right]} \times 100 \tag{25}$$

where $\dot{\mathrm{E}}\mathrm{x}_c(t)$ stands for hourly exergy gain from series connected NPCETCs/NETCs which can be calculated as:

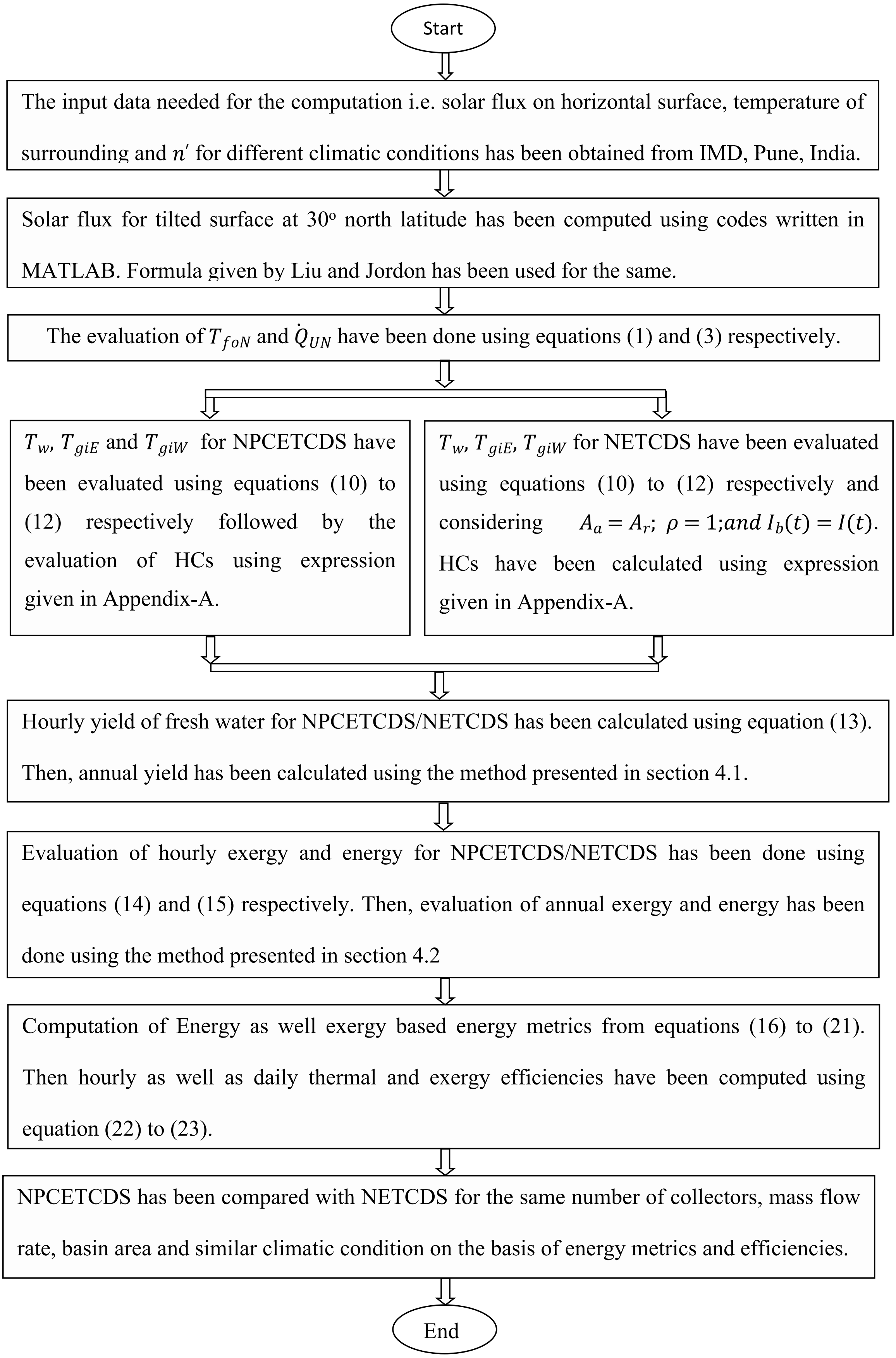
$$\dot{\mathrm{E}}\mathrm{x}_c(t) = \left(\dot{m}_f \times \mathrm{C}_f\right)\left[\left(T_{\text{foN}} - T_{\text{fi}}\right) - \left(T_a + 273\right) \times \left(\ln \frac{\left(T_{\text{foN}} + 273\right)}{\left(T_{\text{fi}} + 273\right)}\right)\right] \tag{26}$$

The factor 0.933 has been obtained using the expression given by Petela [31]. It has been used to convert radiation to exergy.

5. Methodology

The methodology for computing different parameters for NPCETCDS/NETCDS can be expressed as follows:

- *Step I*: The input data needed for the calculation of various parameters of NPCETCDS/NETCDS, that is, solar flux, temperature of surroundings of the system (T_a), and number of days (n') for climatic conditions of kinds (a), (b), (c), and (d) have been taken from Indian Metrological Department (IMD), Pune, India. The value of solar flux for tilted plane at 30° north latitude has been calculated considering the formula of Liu and Jordon [32] with the help of program written in MATLAB.
- *Step II*: The evaluation of T_{foN} and $\dot{Q}_{\text{UN}}$ have been done with the help of Eqs. (1) and (3), respectively, followed by the evaluation of T_w, T_{giE}, T_{giW} using Eqs. (10)–(12), respectively. The various heat transfer coefficients (HCs) have been evaluated using expressions for the same presented in Appendix – A.
- *Step III*: The evaluation of hourly production of potable water for the systems has been done using Eq. (13) followed by the evaluation of annual yield with the help of method presented in section 4.1 (Analysis for production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The input data needed for the computation i.e. solar flux on horizontal surface, temperature of surrounding and n' for different climatic conditions has been obtained from IMD, Pune, India.
Solar flux for tilted surface at 30° north latitude has been computed using codes written in MATLAB. Formula given by Liu and Jordon has been used for the same.
The evaluation of T_{foN} and $\dot{Q}_{UN}$ have been done using equations (1) and (3) respectively.
T_w, T_{giE} and T_{giW} for NPCETCDS have been evaluated using equations (10) to (12) respectively followed by the evaluation of HCs using expression given in Appendix-A.
T_w, T_{giE}, T_{giW} for NETCDS have been evaluated using equations (10) to (12) respectively and considering $A_a = A_r;\ \rho = 1; and\ I_b(t) = I(t)$. HCs have been calculated using expression given in Appendix-A.
Hourly yield of fresh water for NPCETCDS/NETCDS has been calculated using equation (13). Then, annual yield has been calculated using the method presented in section 4.1.
Evaluation of hourly exergy and energy for NPCETCDS/NETCDS has been done using equations (14) and (15) respectively. Then, evaluation of annual exergy and energy has been done using the method presented in section 4.2
Computation of Energy as well exergy based energy metrics from equations (16) to (21). Then hourly as well as daily thermal and exergy efficiencies have been computed using equation (22) to (23).
NPCETCDS has been compared with NETCDS for the same number of collectors, mass flow rate, basin area and similar climatic condition on the basis of energy metrics and efficiencies.
End

of potable water). Similarly, exergy and energy for NPCETCDS/NETCDS have been evaluated with the help of Eqs. (14) and (15), respectively.

- *Step IV*: The computation of energy metrics for NPCETCDS/NETCDS has been done using Eqs. (16)–(21). Similarly, thermal efficiency and exergy efficiency have been computed using Eqs. (22) and (23), respectively.
- *Step V*: NPCETCDS has been compared with NETCDS for the same number of collectors, flow of fluid mass per unit time, basin area, and similar climatic condition on the basis of energy metrics and efficiencies.

For better understanding the methodology for numerical computation of NPCETCDS/NETCDS and their subsequent comparison, flow chart can be drawn as follows:

6. Results and discussion

All concerned equations and data needed for the evaluation, that is, hourly solar flux, temperature of surrounding, and mean wind velocity have been given as input to computer codes written in MATLAB. The hourly solar flux on horizontal surface, temperature of surrounding and value of n' for four kinds of climatic cnditions of New Delhi in different months of year have been taken from IMD Pune, India. Values of mean wind velocity for different months of year and capital needed for NPCETCDS and NETCDS are shown in Tables 2 and 7, respectively. The computation has been done for eight PCETCs, flow of fluid mass per unit time ($\dot{m}_f$) = 0.012 kg s^{-1}, and water depth = 0.14 m. The output of computer codes written in MATLAB has been obtained and they have been presented as Figs. 4 and 5 and Tables 3–8.

Fig. 3 represents the variation of temperature of surrounding, global solar flux, and beam solar flux. The variation of various temperatures has been shown in Fig. 4. From this figure, it is seen that the value of T_{foN} is higher than the value of T_w because water from the outlet of *N*th collectors flows to the basin where it get mixed with the water kept in basin which is at comparatively lower temperature. Further, the temperature of condensing cover made up of glass is less than the temperature of water mass in basin because condensing cover remains in touch with atmospheric and heat energy is being lost to surrounding atmospheric through convective and radiative heat transfer modes. A temperature difference is created between water surface and inner surface of glass cover and this temperature difference is responsible for evaporation of water. This evaporated water is converted into freshwater by rejecting its latent heat at the inside plane of glass cover and moves down under gravity to the channel fixed at the lower side of solar distiller.

Fig. 5 represents the variation of different HCs for NPCETCDS for a typical day in the month of May. It is observed from Fig. 5 that the value of evaporative HC is highest between 5 pm and 6 pm. It happens because evaporative

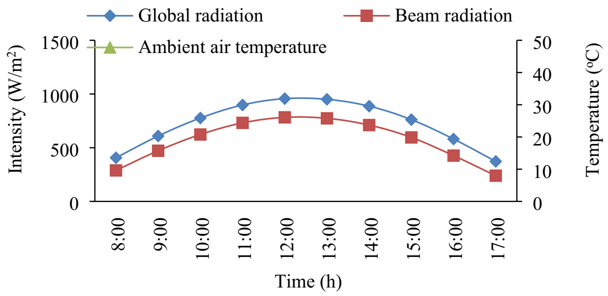

Fig. 3. Hourly solar flux on the surface in horizontal position and surrounding atmospheric temperature for an archetypal day of May.

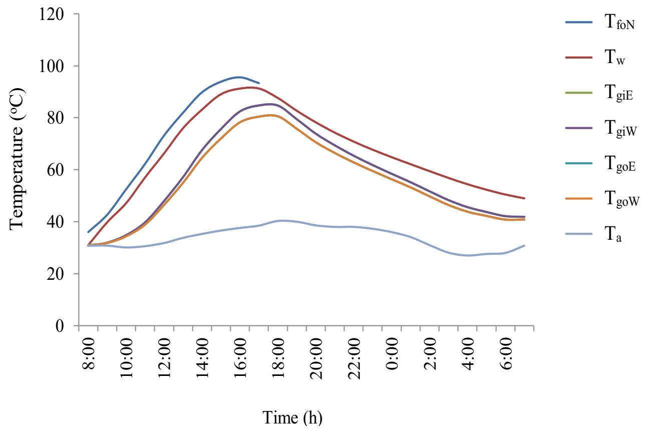

Fig. 4. Variation of different temperatures for NPCETCDS for an archetypal day of May (N = 8).

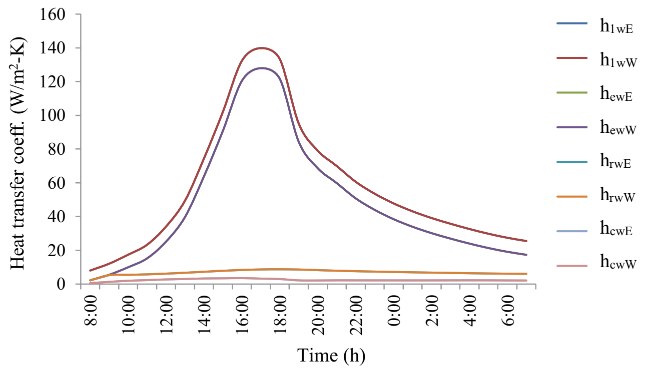

Fig. 5. Variation of different HTCs of NPCETCDS for an archetypal day of May (N = 8).

HC is inversely proportional to the difference in values of T_w and T_{gi} and the difference of values of T_w and T_{gi} is minimum at that time. Further, radiative and convective HCs are very small and they are responsible for losses as they do not

Table 2
Average wind velocity for each month of year for NPCETC/NETCDS

Month	January	February	March	April	May	June	July	August	September	October	November	December
Velocity (m s^{-1})	2.77	3.13	3.46	3.87	4.02	4.11	3.39	2.91	2.85	2.16	1.83	2.40

Table 3
Daily, monthly, and annual yield for NPCETCDS

Month	Weather condition (type a)			Weather condition (type b)			Weather condition (type c)			Weather condition (type d)			Monthly yield
	Y_a	n_a	m_a	Y_b	n_b	m_b	Y_c	n_c	m_c	Y_d	n_d	m_d	
January	21.78	3	65.33	19.87	8	158.99	6.03	11	66.38	1.43	9	12.87	303.57
February	21.33	3	63.98	20.52	4	82.09	6.19	12	74.32	1.20	9	10.84	231.22
March	23.52	5	117.59	24.76	6	148.56	10.45	12	125.35	5.10	8	40.77	432.26
April	25.96	4	103.82	26.34	7	184.40	11.88	14	166.34	9.72	5	48.62	503.18
May	26.05	4	104.18	20.65	9	185.81	14.85	12	178.15	8.51	6	51.06	519.21
June	24.88	3	74.63	20.88	4	83.52	12.62	14	176.61	4.88	9	43.89	378.65
July	21.65	2	43.29	17.73	3	53.20	12.61	10	126.13	4.12	17	69.97	292.60
August	20.98	2	41.97	19.26	3	57.77	9.79	7	68.50	4.31	19	81.97	250.21
September	26.59	7	186.10	23.05	3	69.16	13.94	10	139.36	5.20	10	52.04	446.65
October	21.78	5	108.88	15.83	10	158.32	11.33	13	147.31	3.25	3	9.76	424.26
November	19.57	6	117.42	12.90	10	129.02	4.28	12	51.32	3.56	2	7.11	304.88
December	19.28	3	57.85	16.40	7	114.80	7.33	13	95.27	1.46	8	11.71	279.64
Annual yield (kg)													4,366.34

Table 4
Daily, monthly, and annual yield for NETCDS

Month	Weather condition (type a)			Weather condition (type b)			Weather condition (type c)			Weather condition (type d)			Monthly yield
	Y_a	n_a	m_a	Y_b	n_b	m_b	Y_c	n_c	m_c	Y_d	n_d	m_d	
January	6.11	3	18.32	5.67	8	45.39	2.58	11	28.36	1.23	9	11.07	103.13
February	6.39	3	19.18	6.69	4	26.78	2.90	12	34.75	1.31	9	11.79	92.49
March	8.55	5	42.75	9.75	6	58.50	5.09	12	61.06	4.22	8	33.77	196.08
April	11.50	4	46.01	12.25	7	85.78	7.39	14	103.42	7.65	5	38.27	273.48
May	12.57	4	50.28	12.53	9	112.76	11.20	12	134.37	8.69	6	52.11	349.52
June	11.78	3	35.35	12.44	4	49.74	10.01	14	140.16	6.44	9	58.00	283.25
July	10.73	2	21.46	10.96	3	32.87	8.61	10	86.08	5.80	17	98.52	238.93
August	9.47	2	18.93	10.37	3	31.12	7.45	7	52.14	5.17	19	98.21	200.41
September	11.91	7	83.37	11.55	3	34.64	9.13	10	91.29	5.60	10	56.03	265.34
October	8.35	5	41.75	7.17	10	71.69	5.11	13	66.41	3.20	3	9.60	189.45
November	6.92	6	41.50	5.16	10	51.61	2.48	12	29.75	2.36	2	4.71	127.58
December	5.90	3	17.70	4.76	7	33.33	3.00	13	39.06	1.36	8	10.89	100.98
Annual yield (kg)													2,420.64

contribute to the generation of freshwater. The evaporative HC is responsible for the generation of freshwater.

Table 3 represents the computation of daily, monthly, and annual production of freshwater for NPCETCDS. Table 4 represents the computation of daily, monthly, and annual production of freshwater for NETCDS. Eq. (13) has been used for the evaluation of production of freshwater from NPCETCDS/NETCDS. It is observed from Table 3 that the maximum value of monthly freshwater production occurs in the month of May. It happens because daily yield is also maximum in the month of May due to better climatic condition in the month of May as number of days for kinds a and b climatic condition combined together is highest. Further, minimum value of monthly freshwater production occurs in the month of February. It happens because of the poor weather condition in the month of February. The value of annual production of freshwater from NPCETCDS is higher by 44.56% than the annual production of freshwater from NETCDS. It happens because higher amount of heat is added to the basin of solar still by NPCETCs than NETCs due to the presence of parabolic concentrator surface in the case of NPCETCDS.

Fig. 6 represents the variation of monthly energy output of NPCETCDS and NETCDS. It is observed from Fig. 6 that the maximum value of monthly energy output occurs in the month of May and minimum value of monthly

Table 5
Daily, monthly, and annual thermal exergy for NPCETCDS

Month	Weather condition (type a)			Weather condition (type b)			Weather condition (type c)			Weather condition (type d)			Monthly exergy
	Ex_a	n_a	Exm_a	Ex_b	n_b	Exm_b	Ex_c	n_c	Exm_c	Ex_d	n_d	Exm_d	
January	2.25	3	6.74	1.85	8	14.80	0.25	11	2.76	0.03	9	0.24	24.53
February	1.94	3	5.82	1.82	4	7.29	0.23	12	2.77	0.02	9	0.17	16.05
March	2.17	5	10.83	2.35	6	14.12	0.47	12	5.63	0.15	8	1.18	31.76
April	2.34	4	9.36	2.40	7	16.77	0.48	14	6.67	0.34	5	1.71	34.51
May	2.20	4	8.80	1.43	9	12.85	0.70	12	8.45	0.24	6	1.45	31.54
June	2.10	3	6.31	1.50	4	5.98	0.51	14	7.14	0.10	9	0.92	20.35
July	1.80	2	3.59	1.21	3	3.62	0.56	10	5.57	0.56	17	9.47	22.26
August	1.84	2	3.67	1.53	3	4.60	0.41	7	2.86	0.10	19	1.97	13.11
September	2.65	7	18.57	2.07	3	6.22	0.75	10	7.48	0.13	10	1.29	33.56
October	2.10	5	10.49	1.13	10	11.31	0.54	13	7.07	0.07	3	0.21	29.08
November	1.85	6	11.13	0.74	10	7.43	0.13	12	1.50	0.09	2	0.19	20.24
December	1.74	3	5.22	1.16	7	8.10	0.32	13	4.22	0.03	8	0.20	17.74
Annual exergy (kWh)													294.75

Table 6
Daily, monthly, and annual thermal exergy for NETCDS

Month	Weather condition (type a)			Weather condition (type b)			Weather condition (type c)			Weather condition (type d)			Monthly exergy
	Ex_a	n_a	Exm_a	Ex_b	n_b	Exm_b	Ex_c	n_c	Exm_c	Ex_d	n_d	Exm_d	
January	0.25	3	0.76	0.23	8	1.81	0.07	11	0.72	0.02	9	0.19	3.48
February	0.24	3	0.72	0.26	4	1.04	0.07	12	0.83	0.02	9	0.19	2.78
March	0.34	5	1.69	0.42	6	2.50	0.15	12	1.76	0.11	8	0.87	6.82
April	0.45	4	1.79	0.50	7	3.48	0.21	14	2.95	0.22	5	1.12	9.34
May	0.47	4	1.87	0.46	9	4.17	0.38	12	4.58	0.25	6	1.47	12.09
June	0.45	3	1.35	0.49	4	1.97	0.34	14	4.76	0.16	9	1.46	9.53
July	0.42	2	0.84	0.44	3	1.31	0.29	10	2.89	0.15	17	2.50	7.55
August	0.38	2	0.77	0.45	3	1.34	0.26	7	1.80	0.14	19	2.66	6.57
September	0.52	7	3.61	0.49	3	1.47	0.33	10	3.29	0.15	10	1.45	9.81
October	0.33	5	1.63	0.25	10	2.51	0.14	13	1.86	0.07	3	0.20	6.21
November	0.27	6	1.63	0.17	10	1.68	0.05	12	0.63	0.05	2	0.10	4.04
December	0.23	3	0.69	0.16	7	1.14	0.08	13	1.02	0.02	8	0.18	3.03
Annual exergy (kWh)													81.24

energy occurs in the month of February. It happens because of the similar variation in the values of monthly freshwater production. Energy output is directly proportion to the production of freshwater as evident from Eq. (15).

Table 5 represents the computation of daily, monthly, and annual exergy output from NPCETCDS for eight PCETCs, flow of fluid mass per unit time ($\dot{m}_f$) = 0.012 kg s^{-1} and water depth = 0.14 m. Eq. (14) has been used to evaluate exergy output. It is observed from Table 5 that the maximum and minimum values of monthly exergy output takes place in April and February, respectively. The maximum value of monthly exergy occurs in April due to better performance of NPCETCDS under kind b climatic condition. The minimum value of monthly exergy occurs in the month of August due to poor weather condition in the month of February. Table 6 represents the computation of daily, monthly, and annual exergy output from NETCDS for eight ETCs, flow of fluid mass per unit time ($\dot{m}_f$) = 0.012 kg s^{-1} and water depth = 0.14 m. Exergy output for NETCDS has been calculated with the help of Eq. (14). It is observed from Table 6 that the maximum and minimum values of monthly exergy output takes place in May and February, respectively. One can conclude from Tables 5 and 6 that the value of monthly exergy output for NPCETCDS is higher for NPCETCDS by 72.43% than the corresponding value for NETCDS. It happens because

Table 7
Embodied energy (E_{in}), energy payback time (EPBT), and energy production factor (EPF) for double slope active solar distillation system

Name of component	NPCETCDS	NETCDS
	Embodied energy (kWh)	Embodied energy (kWh)
Double slope solar still	1,483.90	1,483.90
Collector (N = 8)	3,084.30	880.29
Others	23	20
NPCETCDS		
Total embodied energy = 4,591.2 kWh		
Annual yield = 4,366.34 kg		
Annual energy output from NPCETCDS = 2,910.89 kWh		
Annual exergy output from NPCETCDS = 294.75 kWh		
Energy payback time (EPBT) based on energy = 1.58 y		
Energy payback time (EPBT) based on exergy = 15.57 y		
Energy production factor (EPF) based on energy = 0.63/y		
Energy production factor (EPF) based on exergy = 0.064/y		
NETCDS		
Total embodied energy = 2,384.19 kWh		
Annual yield = 2,420.64 kg		
Annual energy available from solar still = 1,613.76 kWh		
Annual exergy available from solar still = 81.24 kWh		
Energy payback time (EPBT) based on energy = 1.48 y		
Energy payback time (EPBT) based on exergy = 29.35 y		
Energy production factor (EPF) based on energy = 0.67/y		
Energy production factor (EPF) based on exergy = 0.034/y		

Table 8
Life cycle conversion efficiency (LCCE) for NPCETCDS/NETCDS

	NPCETCDS	NETCDS
Life (year)	50	50
Energy output in kWh	2,910.89	1,613.76
Embodied energy in kWh	4,591.2	2,384.19
Solar energy for life time (kWh)	600,819.62	300,286.86
Life cycle conversion efficiency (LCCE) based on energy	0.2346	0.2607
Exergy output in kWh	294.75	81.24
Solar exergy for life time in kWh	558,762.20	279,266.80
Life cycle conversion efficiency (LCCE) based on exergy	0.0181	0.0087

higher amount of heat is added by collectors to the basin of solar still in the case of NPCETCDS than NETCDS due to the integration of parabolic concentrator surface to ETC in the case of NPCETCDS.

Table 7 represents the computation of EBE, energy, and exergy based energy payback time, energy, and exergy based energy production factor for NPCETCDS/NETCDS at eight number of collectors, 0.012 kg s^{-1} flow of fluid mass per unit time and 0.14 m water depth. It is observed from the table that EBE is higher by 48.07% for NPCETCDS than NETCDS due to geometry of the proposed system as parabolic surface is present in NPCETCDS, but parabolic surface is absent in NETCDS. It is further seen that the energy payback time on the basis of energy (ET_e) is higher by 6.33% for NPCETCDS than NETCDS; whereas, energy payback time on the basis of exergy (ET_{ex}) is lower by 88.50% for NPCETCDS than NETCDS. The reason being that heat is available at higher temperature in the case of NPCETCDS; whereas heat is available at comparatively lower temperature in the case of NETCDS. Heat at higher temperature is of better quality than the heat at lower temperature. So, a respectable amount of energy is produced by NETCDS; however, exergy produced is comparatively lower. So, the ratio of EBE to annual energy output is higher for NPCETCDS; however, ratio of EBE to annual exergy is lower for NPCETCDS. It means, NPCETCDS performs

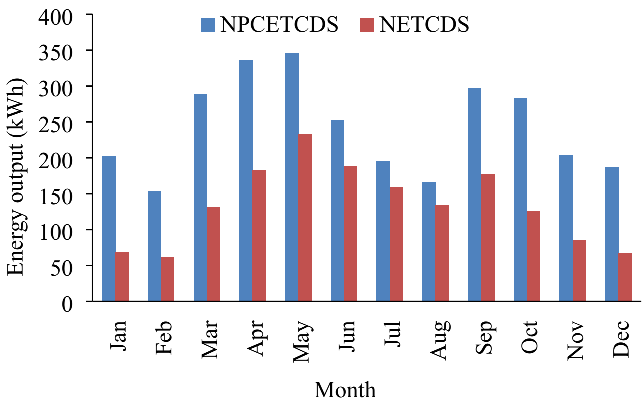

Fig. 6. Variation of monthly energy output of NPCETCDS and NETCDS.

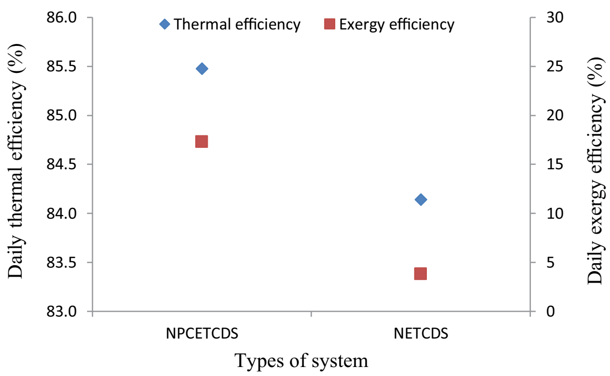

Fig. 7. Comparison of daily thermal and exergy efficiencies for NPCETCDS and NETCDS for an archetypal day of May.

better on the basis of exergy; but poor on the basis of energy. Energy production factor is the reverse of energy payback time. The value of EP_e is lower by 6.35% for NPCETCDS than NETCDS; whereas, value of EP_{ex} is higher by 46.87% for NPCETCDS than NETCDS. The reason being same as that of the reason for variation in the value of ET_e and ET_{ex}.

Table 8 represents the computation of energy and exergy based life cycle conversion efficiencies for NPCETCDS/NETCDS at eight number of collectors, 0.012 kg s^{-1} flow of mass per unit time, and 0.14 m water depth. The value of LCCE is different from the efficiency in the sense that LCCE considers the entire life span of the system. The value of $LCCE_e$ is lower by 6.35% for NPCETCDS than NETCDS; whereas, the value of $LCCE_{ex}$ is higher by 46.87% for NPCETCDS than NETCDS. The reason for the variation in $LCCE_e$ is that the difference of total energy output for the entire life span and EBE is 44.45% higher; however, total solar energy falling on the system is 50.02% higher for NPCETCDS than NETCDS. Hence, the ratio of numerator and denominator in Eq. (20) comes out to be lower by 6.35% for NPCETCDS. Again, the reason for the variation in $LCCE_{ex}$ is that the difference of total exergy output for the entire life span and EBE is 75.87% higher; however, total solar energy falling on the system is 50.02% higher for NPCETCDS than NETCDS. Hence, the ratio of numerator and denominator in Eq. (20) comes out to be lower by 46.87% for NPCETCDS. Moreover, temperature of energy available is comparatively higher in the case of NPCETCDS than the temperature of energy available in the case of NETCDS. So, quality of energy in the case of NPCETCDS is better and hence $LCCE_{ex}$ is better for NPCETCDS.

Fig. 7 represents the comparison of daily thermal and exergy efficiencies of NPCETCDS and NETCDS for an archetypal day of May for same number of collectors, flow of fluid mass per unit time, water depth, basin area, and similar climatic condition. It has been observed from Fig. 7 that the daily thermal efficiency is higher marginally by 1.56% for NPCETCDS than NETCDS. The reason being that higher amount of heat is added by NPCETCs to the basin as compared to heat added by NETCs to basin due to the presence of parabolic surface in the case of NPCETCDS. It is further seen that the daily exergy efficiency is higher by 78.01% for NPCETCDS than NETCDS. The reason being that heat is available at higher temperature in the case of NPCETCDS.

7. Conclusions

Two systems namely NPCETCDS and NETCDS have been compared theoretically on the basis of energy metrics and efficiency for eight number of collectors, flow of fluid mass per unit time ($\dot{m}_f$) = 0.012 kg s^{-1} and water depth = 0.14 m. On the basis of current research study, the following conclusions have been made:

- NPCETCDS has been found to perform better than NETCDS on the basis of annual production of freshwater, annual energy output, and annual exergy output for same number of collectors, flow of fluid mass per unit time, water depth, basin area, and similar climatic condition.
- Exergy based energy payback time is lower by 88.50%; but energy based energy payback time is higher by 6.33% for NPCETCDS than NETCDS for same number of collectors, flow of fluid mass per unit time, water depth, basin area, and similar climatic condition.
- Exergy based energy production factor is higher by 46.87%; but energy based energy production factor is lower by 6.35% for NPCETCDS than NETCDS for same number of collectors, flow of fluid mass per unit time, water depth, basin area, and similar climatic condition.
- NPCETCDS performs better than NETCDS on the basis of exergy based LCCE; however, NETCDS performs better than NPCETCDS on the basis of energy based LCCE for same number of collectors, flow of fluid mass per unit time, water depth, basin area, and similar climatic condition.
- NPCETCDS performs better than NETCDS on the basis of daily thermal efficiency and daily exergy efficiency for same number of collectors, flow of fluid mass per unit time, water depth, basin area, and similar climatic condition.

Nomenclature

A_b	—	Area of basin, m^2
A_{gE}	—	Area of east glass cover, m^2
A_{gW}	—	Area of west glass cover, m^2

C_f/C_w — Specific heat capacity, J kg^{-1} K
AS — Annual solar energy
C_p — Total present cost of NPCETCDS/NETCDS
C_l — Cost of fabrication for NPCETCDS/NETCDS
C_{NPCETC} — Present cost of NPCETCs
C_{DS} — Present cost of DS
CF — Capital recovery factor
C_{pw} — Unit cost of producing potable water from NPCETCDS/NETCDS
DS — Double slope solar still
$\dot{E}x_{out}$ — Hourly exergy output, kWh
ET — Energy payback time
ETC — Evacuated tubular collector
EP — Energy production factor
$\dot{E}_{out}$ — Hourly energy output
$\dot{E}x_c$ — Hourly exergy output from series connected *N* identical collectors
E_{annual} — Annual energy output
Ex_{annual} — Annual exergy output
EBE — Embodied energy
F' — Collector efficiency factor, dimensionless
HC — Heat transfer coefficient, W m^{-2} K
h_{cw} — Convective heat transfer coefficient from water to inner surface of glass cover, W m^{-2} K
h_{ewE} — Evaporative heat transfer coefficient from water surface to inner surface of east glass cover, W m^{-2} K
h_{ewW} — Evaporative heat transfer coefficient from water surface to inner surface of west glass cover, W m^{-2} K
h_c — Convective heat transfer coefficient, W m^{-2} K
h_{ba} — Heat transfer coefficient from blackened surface to ambient, W m^{-2} K
h_{bw} — Heat transfer coefficient from blackened surface to water mass, W m^{-2} K
h — Heat transfer coefficient, W m^{-2} K
h_{rw} — Radiative heat transfer coefficient from water to inner surface of glass cover, W m^{-2} K
h_r — Radiative heat transfer coefficient, W m^{-2} K
h_{1w} — Total heat transfer coefficient from water surface to inner glass cover, W m^{-2} K
h_{1g} — Total heat transfer coefficient from water surface to inner glass cover, W m^{-2} K
h_{EW} — Radiative heat transfer coefficient from inner surface of east glass cover to inner surface of west glass cover
$I(t)$ — Total solar flux, W m^{-2}
$I_b(t)$ — Beam radiation on collector, W m^{-2}
IC — Initial cost of system
i — Rate of interest
$I_{SE}(t)$ — Solar intensity on east glass cover, W m^{-2}
I_{SW}(t) — Solar intensity on west glass cover, W m^{-2}
K — Thermal conductivity, W m^{-1} K
L_g — Thickness of glass cover, m
LCCE — Life cycle conversion efficiency
L' — Latent heat, J kg^{-1}
L — Length, m
$\dot{m}_f$ — Flow of fluid mass per unit time, kg s^{-1}
$\dot{m}_{ew}$ — Mass of distillate from double slope solar still, kg
N — Number of parabolic concentrator integrated evacuated tubular collector
NPCETCDS — Double slope solar distiller unit augmented with *N* identical parabolic concentrator integrated evacuated tubular collectors
N' — Number of sunshine hours
n' — Number of days
NETCDS — Double slope solar still coupled with *N* alikel ETCs
PCETC — Parabolic concentrator integrated evacuated tubular collectors
p' — Ratio of daily diffuse to daily global irradiation
PF_1 — Penalty factor first, dimensionless
$\dot{Q}_{UN}$ — Useful energy gain for *N* identical collector connected in series, kWh
R_{o1} — Inner radius of outer glass tube of evacuated coaxial glass tube, m
R_{i1} — Inner radius of inner glass tube of evacuated coaxial glass tube, m
R_{i2} — Outer radius of inner glass tube of evacuated coaxial glass tube, m
R_{o2} — Outer radius of outer glass tube of evacuated coaxial glass tube, m
CR — Concentration ratio
r — Radius of copper tube in ETC
ρ — Reflectivity
T_{foN} — Outlet water temperature at the exit of Nth PCETC, °C
T_a — Ambient temperature, °C
T_{giE} — Temperature at inside plane of condensing cover oriented towards east, °C
T_{giW} — Temperature at inside plane of condensing cover oriented towards west, °C
T — Time, h
T_{wo} — Water temperature at t = 0, °C
T_w — Water temperature, °C
U_L — Overall heat transfer coefficient
V — Velocity of air, m s^{-1}

Subscript

b — Basin liner
P — Plate
E — East
eff — Effective
e — Energy
ex — Exergy
f — Fluid
g — Glass
in — Incoming
out — Outgoing
w — Water
W — West

Greek letters

α — Absorptivity (fraction)
η — cfficiency, %
$(\alpha\tau)_{eff}$ — Product of effective absorptivity and transmittivity
σ — Stefan-Boltzmann constant, W m^{-2} K^4

τ — Transmissivity
$\eta_{h,\mathrm{th}}$ — Hourly thermal efficiency
$\eta_{d,\mathrm{th}}$ — Daily thermal efficiency
$\eta_{h,\mathrm{ex}}$ — Hourly exergy efficiency
$\eta_{d,\mathrm{ex}}$ — Daily exergy efficiency

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Appendix – A

$$U_{\text{tpa}} = \left[\frac{R_{o2}\ln\left(\frac{R_{i2}}{R_{i1}}\right)}{K_g} + \frac{1}{C_{\text{ev}}} + \frac{R_{o2}\ln\left(\frac{R_{o2}}{R_{o1}}\right)}{K_g} + \frac{1}{h_o} \right]^{-1} \quad h_{\text{pf}} = 100\ \text{Wm}^{-2}\text{K}^{-1} \quad h_o = 5.7 + 3.8V \tag{A1}$$

$$\text{PF}_1 = \frac{F'h_{\text{pf}}}{F'h_{\text{pf}} + U_{\text{tpa}}} \left(\alpha\tau\right)_{\text{eff}} = \rho\alpha\tau^2\left(\frac{A_a}{A_r}\right) \quad (A_rF_r) = \frac{\dot{m}_f C_f}{U_L}\left[1 - \exp\left(-\frac{2\pi r L U_L}{\dot{m}_f C_f}\right)\right] \tag{A2}$$

$$K_K = 1 - \frac{A_r F_r U_L}{\dot{m}_f C_f} \quad h_{\text{bw}} = 100\ \text{Wm}^{-2}\text{K}^{-1} \quad U_{\text{cE}} = \frac{\frac{K_g}{L_g} h_{1\text{gE}}}{\frac{K_g}{L_g} + h_{1\text{gE}}} \quad U_{\text{cW}} = \frac{\frac{K_g}{L_g} h_{1\text{gW}}}{\frac{K_g}{L_g} + h_{1\text{gW}}} \tag{A3}$$

$$U_2 = h_{1\text{wW}}\frac{A_b}{2} + h_{\text{EW}}A_{\text{gW}} + U_{\text{cW}}A_{\text{gW}} \quad R_1 = \alpha'_g I_{SE} + U_{\text{cE}}T_a \quad R_2 = \alpha'_g I_{\text{SW}} + U_{\text{cW}}T_a \tag{A4}$$

$$A_1 = R_1 U_2 A_{\text{gE}} + R_2 h_{\text{EW}} A_{\text{gW}} \quad A_2 = h_{1\text{wE}}\frac{A_b}{2} + \frac{h_{\text{Ew}}}{U_2} h_{1\text{wW}}\frac{A_b}{2} \tag{A5}$$

$$U_1 = h_{1\text{wE}}\frac{A_b}{2} + h_{\text{EW}}A_{\text{gE}} + U_{\text{cE}}A_{\text{gE}} \quad P = U_2U_1 - \frac{h_{\text{EW}}^2 A_{\text{gW}}}{A_{\text{gE}}} \quad B_1 = \frac{\left(R_2 P + h_{\text{EW}}A_1\right)A_{\text{gW}}}{U_2 A_{\text{gE}}} \tag{A6}$$

$$B_2 = \frac{\text{Ph}_{1\text{wW}}\frac{A_b}{2} + h_{\text{EW}}A_{\text{gW}}A_2}{U_2 A_{\text{gE}}} \quad h_1 = \frac{h_{\text{bw}}}{2\left(h_{\text{bw}+h_{ba}}\right)} \quad U_b = \frac{h_{\text{ba}}h_{\text{bw}}}{h_{\text{ba}} + h_{\text{bw}}} \tag{A7}$$

$$a = \frac{1}{M_w C_w}\left[(A_rF_r)U_L\frac{\left(1-K_k^N\right)}{\left(1-K_k\right)} + U_bA_b + \left(h_{1\text{wE}} + h_{1\text{wE}}\right)\frac{A_b}{2} - \left(\frac{h_{1\text{wE}}A_2}{P}\right)\frac{A_b}{2} - \left(\frac{h_{1\text{wW}}B_2}{P}\right)\frac{A_b}{2}\right] \tag{A8}$$

$$f(t) = \frac{1}{M_w C_w}\left[\left(\frac{\alpha'_w}{2} + h_1\alpha'_b\right)A_b\left(I_{\text{SE}}(t) + I_{\text{SW}}(t)\right) + U_bA_bT_a + \frac{\left(h_{1\text{wE}}A_1 + h_{1\text{wW}}B_1\right)}{P}\frac{A_b}{2} + \left(\text{PF}_1\right)\left(\alpha\tau\right)_{\text{eff}}\frac{\left(1-K_k^N\right)}{\left(1-K_k\right)}I_b + (A_rF_r)U_L\frac{\left(1-K_k^N\right)}{\left(1-K_k\right)}T_a\right] \tag{A9}$$

$$h_{\text{ewE}} = 16.273\times10^{-3}h_{\text{cwE}}\left[\frac{P_w - P_{\text{giE}}}{T_w - T_{\text{giE}}}\right] \text{(Cooper [33])} \tag{A10}$$

$$h_{\text{ewW}} = 16.273\times10^{-3}h_{\text{cwW}}\left[\frac{P_w - P_{\text{giW}}}{T_w - T_{\text{giW}}}\right] \text{(Cooper [33])} \tag{A11}$$

$$h_{\text{cwE}} = 0.884\left[\left(T_w - T_{\text{giE}}\right) + \frac{\left(P_w - P_{\text{giE}}\right)\left(T_w + 273\right)}{268.9\times 10^3 - P_w}\right]^{\frac{1}{3}} \text{ (Dunkle, [34])} \tag{A12}$$

$$h_{\text{cwW}} = 0.884\left[\left(T_w - T_{\text{giW}}\right) + \frac{\left(P_w - P_{\text{giW}}\right)\left(T_w + 273\right)}{268.9\times 10^3 - P_w}\right]^{\frac{1}{3}} \text{ (Dunkle [34])} \tag{A13}$$

$$P_w = \exp\left[25.317 - \frac{5,144}{T_w + 273}\right] \qquad P_{\text{giE}} = \exp\left[25.317 - \frac{5,144}{T_{\text{giE}} + 273}\right] \qquad P_{\text{giW}} = \exp\left[25.317 - \frac{5,144}{T_{\text{giW}} + 273}\right] \tag{A14}$$