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Sensitivity analysis of a solar still of a single slope type included with *N* similar evacuated tubular collectors having series connection

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ABSTRACT

In this research paper, an investigation on solar still of single slope type included with N similar evacuated tubular collectors having a series connection by incorporating sensitivity analysis has been performed. The analysis for sensitivity has been done using one at a time method by feeding all expressions of different parameters to computer code written in MATLAB – 2015a for the May month of New Delhi climatic situation. Freshwater yielding and exergy gain values have been estimated for dissimilarities of mass flow rate maintaining other parameters at the input of system constant and this procedure has been repeated till estimation is completed for all parameters at the input of the system. All results so obtained have been 2D plotted. The freshwater yielding for the considered system has been estimated to be the most sensitive with regards to θ; whereas, exergy gain has been found to be the most sensitive with regards to N having mean sensitivity figure values as 0.74 and 1.31 in that order. Sensible conclusions have been presented based on the current analysis.

Keywords: Sensitivity analysis; ETC; Solar still; Exergy gain; Potable water yielding

1. Introduction

The analysis of solar still of single slope type included with N similar solar collectors normally called as active solar still of single slope type is the need of time as it has the capability to provide one of the best solutions for mitigating the existing concern over fresh water scarcity throughout the world. The working principle of active solar still of single slope type is based on green house effect. Its structure consists of box type construction having inclined tope surface and the box which is known as basin is connected to solar collectors for supplying heat to basin. The purification of dirty water using solar energy technology is simple to understand. It does not emit polluting elements. This feature makes the solar system as environment friendly. The solar energy technology based water purification unit uses solar energy for its functioning as most of the solar systems are self-sustainable; whereas, other water purifiers uses the technology which needs conventional source of energy for its working and pollutes the surrounding. The sensitivity investigation for solar technology based active water purifiers tells the significance of parameters at the input of system for getting particular output. So, the designer of system will have knowledge in advance about the effect of input parameters on the selected output and can readily monitor input parameters as per the requirement of customer/user. The sensitivity investigation on active solar still of

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single slope type can be carried out using one at a time method which consists of finding the output values corresponding to the dissimilarity in one input parameter while maintaining other input parameters as constant followed by the repetition of this procedure till the estimation for all input parameters is completed. Then, sensitivity figure is estimated as the ratio of percentage change in output parameter to the percentage change in input parameter followed by 2D plotting of results so obtained.

The application of solar energy technology for purification of dirty water assists in the growth of eco friendly ambiance in broad spatial coverage of the earth. It is the suitable application for remote locations on the earth. The study tells that 2/3rd population of the world is going to face the scarcity of fresh water by 2025 because of the unavailability of various natural resources as only less than 1% of the available water is accessible and this small percentage of water is also getting polluted because of an assortment of anthropogenic activities. The sustainable defense of fresh water for drinking and other uses is the main challenge in the contemporary situation. Also the issue of drought and flood are challenging and it occurs throughout the globe. In the near future, the fresh water quality is expected to be poor and not fit for drinking as per UN report.

The solar energy technology based water purification system is categorized as passive type and active type. If solar collectors are included with passive type solar still, active type solar still is obtained. The working principle of passive type solar still is based on green house effect and it does not take heat from outside heat collection system. The passive type solar still faces the issue of low fresh water yielding and this problem of passive type solar still is resolved by incorporating solar collector to passive type solar still. When solar collectors are incorporated with passive type solar still, the resulting solar system is known as active type solar still and the temperature of water in active type solar still is higher as compared to passive type solar still. Due to increased temperature in the case of active type solar still, increased fresh water yielding is obtained. The active type solar energy based water purifier (SEBWP) came into existence in 1983 [1] and from that time, many new designs have been reported by various researchers around the globe.

Rai and Tiwari [1] reported the enhancement in yield of active type SEBWP by incorporating one conventional flat plate collector (FPC) over passive type SEBWP of the same basin area due to the addition of heat to the basin in active mode of operation. This water purifier was not self sustainable as the pump needed some electric power for working which was supplied through grid. The active type SEBWP in the forced mode of operation can be made self sustainable by incorporating solar panel. Kumar and Tiwari [2] proposed the integration of PVT with FPC for supplying heat to basin of passive type SEBWP taking inspiration from the work of Kern and Russell [3]. It was reported by Kern and Russell that the electrical efficiency of solar panel got increased upon integration of solar panel with solar collector due the removal of heat by fluid passing below the panel. Kumar and Tiwari reported the improvement in output by 3.5 times over the similar passive type SEBWP due to the addition of heat by two collectors in which only one of them was integrated with PVT for making the system self-sustainable. The work of Kumar and Tiwari was extended by Singh et al. [4] for DS type SEBWP in active mode. Further, Singh et al. [5] and Tiwari et al. [6] reported the experimental investigation of SEBWP by incorporating two FPCs in which both FPCs were partially integrated with PVT. They reported an enhancement in DC electrical output; however, the yield of fresh water was less as compared to the system reported by Kumar and Tiwari [2]. The heat gain was less because more area of FPCs was covered by PVT. Further, active type SEBWP was studied under optimized situation [7–11]. It was reported that the DS type SEBWP under optimized condition by incorporating N alike PVT-FPCs had 74.66% higher ENPBT over passive type DS-SEBWP. The value of exergoeconomic parameter for single slope type SEBWP was found to be 47.37% higher than the passive type single slope SEBWP of same basin area. Sahota et al. [12] reported the use of nanofluid in DS type SEBWP in active mode for enhancing the fresh water output. Carranza et al. [13] have experimentally investigated the performance of DS type SEBWP loaded with nanofluid by incorporating preheating of saline water and concluded that water yield increases due to better thermophysical properties of nanofluid as compared to base fluid. Kouadri et al [14] have investigated solar still by incorporating zinc and copper oxides for the location of Algeria and compared the yield with conventional SEBWP and concluded that the water yeld was improved by 79.39% due to having better thermophysical characteristic of nanofluid.

The output of SEBWP could further be enhanced by changing the design of solar collector which could absorb higher amount of heat from the sun or by changing the design of solar still. PVT integrated FPC could gain higher heat if some concentrating part was integrated with FPC. With this concept in mind, Atheaya et al. [15] proposed PVT integrated compound parabolic concentrator collector (CPC) and reported its thermal model which was further extended by Tripathi et al. [16] for N collectors connected in series and loop was opened. Singh and Tiwari [17–19], Gupta et al. [20,21], Singh et al. [22,23] and Sharma et al. [24] investigated SEBWP of basin type by incorporating characteristic equations development and concluded that SEBWP of double slope type performs better than SEBWP of single slope type under optimized conditions of mass flow rate and number of collectors at 0.14 m water depth due to better distribution of solar energy in the case of double slope type. Prasad et al. [25], Bharti et al. [26], Singh [27] investigated SEBWP of double slope type from sensitivity viewpoint and concluded that the sensitivity analysis helps designer and installer of solar systems as which parameter should be focused more for a particular application.

The heat gain by solar collector can be enhanced by providing evacuated tubes because convection loss does not take place through vacuum. Sampathkumar et al. [28] investigated the SEBWP by incorporating evacuated tubular collector and reported an increase of 129% over the SEBWP of the same basin area due to the addition of heat to the basin by collectors. An investigation of SEBWP in natural mode of operation by incorporating evacuated tubes was done by Singh et al. [29] and reported exergy efficiency lying in the range of 0.15% to 8%. Further, an investigation of SEBWP incorporated with evacuated tubes was done in forced mode of operation by inserting pump between collector and basin and reported enhanced fresh water output as compared to the similar system operated in natural mode due to better circulation of fluid in the forced mode of operation [30]. Mishra et al. [31] reported characteristic equation development for N alike series connected ETCs. The work reported by Mishra et al. [31] was further extended by Singh et al. [32–34]. The thermal modeling of basin type SEBWP by incorporating N alike ETCs was reported by them and comparison was also made between single slope active water purifier and DS type SEBWP in active mode taking energy, exergy, energy metrics, exergoeconomic and enviroeconomic parameters as basis. Issa and Chang [35] further extended the work of singh et al. by connecting ETCs in mixed mode of operation experimentally and reported enhanced output as compared to similar set up in passive mode due to heat addition by collectors in active mode. Moreover, Singh and Al-Helal [36], Singh [37] and Sharma et al. [38,39] reported development of characteristic equations and the observations based on the energy metrics for SEBWP by incorporating evacuated tubular collector as well as compound parabolic concentrator integrated evacuated tubular collector.

Patel et al. [40–42] have reviewed SEBWP recently by incorporating different types of collectors. Further, Singh et al. [43] reviewed SEBWP by incorporating different types of collectors and loaded with nanofluid with an aim to find the effect of nanofluid on the performance of active SEBWP. Nanofluid is obtained by mixing a small amount of nanoparticles to water. The effect of adding nanoparticles to water in SEBWP is to increase the output (potable water and exergy) of SEBWP. The better performance of nanofluid loaded SEBWP than loaded with water is due to the possession of better thermo-physical characteristic of nanofluid as compared to water. Bansal et al. [44] have reported the mini review of changing the material of absorber on the performance of solar still. Shankar et al. [45] have studied ETC integrated SEBWP in natural as well forced mode and concluded that forced mode is better for environment as higher carbon credit was observed in forced mode due to more addition of heat to basin in the case of forced mode. Abdallah et al. [46] have investigated spherical and pyramid basin SEBWP and concluded that the spherical basin SEBWP gave 57.1% higher water yield due to better utilization of solar radiation in the case of spherical basin.

From the extant research, it is clear that the sensitive, thermal and exergy efficiencies analyses of solar still of single slope type included with N similar evacuated tubular collectors having series connection (NETCSS) have not been touched and conveyed round the world by any researcher. Hence, the proposed research deals with the sensitive, thermal and exergy efficiencies analyses of NETCSS. The prime objects of present research work are as under:

- To inspect the outcomes by varying mass flow rate to see its effect on fresh water yielding as well as exergy gain maintaining other parameters at the input of NETCSS constant followed by 2D plotting and the estimation of sensitivity figures.
- To examine the outcomes by varying N value to see its effect on the fresh water yielding as well as exergy gain for the chosen value of mass flow rate, collector inclination and water depth followed by 2D plotting and sensitivity figures estimation.
- To inspect the influence of variation in water depth on fresh water yielding as well as exergy gain for NETCSS taking other parameters at the input as constant and estimation of corresponding sensitivity figures.
- To find the influence of changing collector inclination on fresh water yielding and exergy gain for NETCSS maintaining other parameters at the input of the system constant followed by estimation of sensitivity figures.

2. System description

The detailed illustration of NETCSS and sectional interpretation of 1st ETC collector have been revealed as Figs. 1 and 2 in that order. The used constraints and their corresponding values are tabulated in Table 1. The average wind velocity has been approximately taken as 4.02 m/s. During the study, for achieving higher water temperature at the exit side of *N*th ETC; ETCs are joined in series to improve the gain of heat so that maximum heat can be transferred to water in basin of NETCSS. The distiller unit basin is covered with a transparent condensation cover through which, solar irradiance is transmitted to the basin after reflection and absorption. Further, the fraction of transmitted solar irradiance at water surface first reflected by the water surface, some is getting absorbed and remaining is being transferred to the basin liner. The basin liner is a blackened surface and absorbs almost the total solar irradiance transmitted through the water. Thereby the basin liner gets heated and transfers its heat to the available water depth in the basin. The basin water is also circulating through the coupled solar collectors; in this way an additional indirect heat is also being added to the basin water. Hereafter, the temperature of basin water increases by the direct and indirect heating and evaporation of water started inside the basin. The evaporated water further gets condensed on the inner surface of condensation cover with essential phenomena of film condensation. Film condensation is required to maintain the transmittance of the transparent condensing cover for improving direct basin water heating. The condensed water trickles on the inner surface of condensing cover by the gravity effect as the condensing cover is inclined and collected through the channels provided at the corner. Finally, distilled water from the channels can be collected into the storage unit for further use.

3. Mathematical Equations for NETCSS

Mathematical modeling of NETCSS means writing equations for all its components by equating input energy to output energy. Following assumptions presented in Gupta et al. [20], the mathematical modeling can be done as follows:

3.1. Heat gain for NETCs

The useful heat gain from NETCs and temperature at the outlet of *N*th ETC can be transcribed as [31,34].

Table 1
Specifications of single slope solar still integrated with N identical evacuated tubular collectors (NETCSS)

Component	Specification	Component	Specification
Single slope active solar still			
Length	2 m	Cover material	Glass
Width	1 m	Orientation	South
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-K
Material of body	GRP	Thickness of insulation	0.1 m
Material of stand	GI	K_i	0.166 W/m-K
ETC			
Type and no. of collectors	ETC, N	α_p	0.8
DC motor rating	12 V, 24 W	F'	0.968
Radius 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 ETC 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		

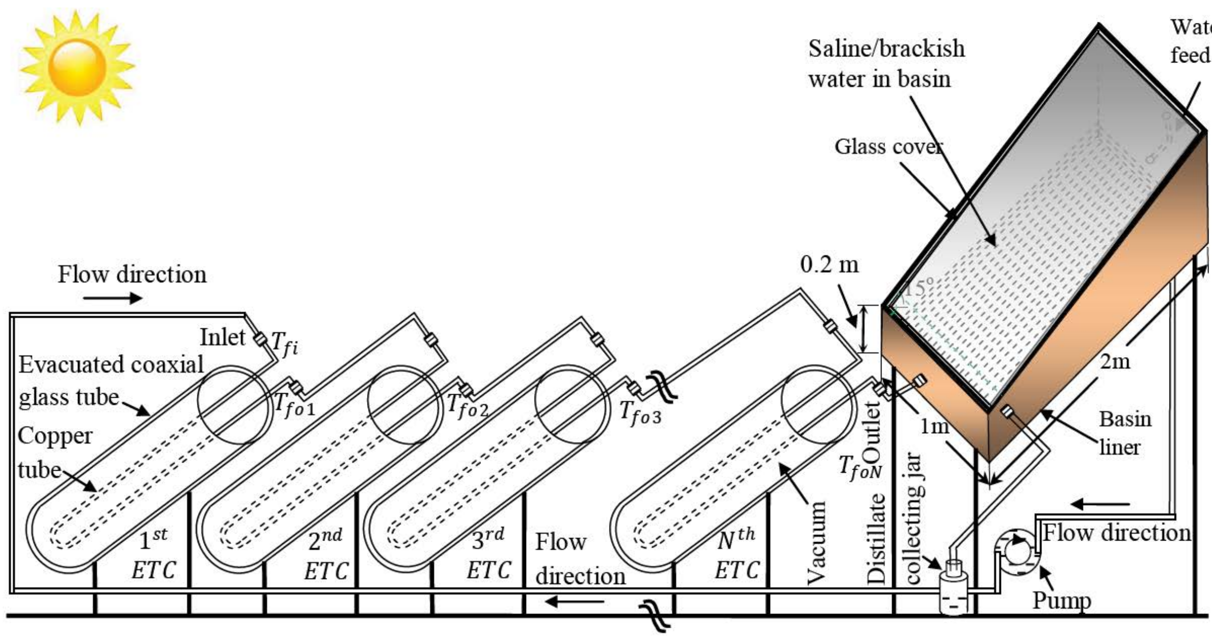

Fig. 1. N identical ETCs integrated single slope solar distiller unit (NETCSS).

$$\dot{Q}_{uN} = \frac{\left(1-K_k^N\right)}{\left(1-K_k\right)}\left(AF_R(\alpha\tau)\right)_1 I(t) + \frac{\left(1-K_k^N\right)}{\left(1-K_k\right)}\left(AF_RU_L\right)_1\left(T_{fi}-T_a\right) \quad (1)$$

$$T_{foN} = \frac{\left(AF_R(\alpha\tau)\right)_1}{\dot{m}_fC_f}\frac{\left(1-K_k^N\right)}{\left(1-K_k\right)}I(t) + \frac{\left(AF_RU_L\right)_1}{\dot{m}_fC_f}\frac{\left(1-K_k^N\right)}{\left(1-K_k\right)}T_a + K_k^N T_{fi} \quad (2)$$

where T_{foN} and T_{fi} are temperatures at the exit side of *N*th ETC and at the inlet of 1st ETC in that order. Here, T_{fi} will be same as T_w due to the fact that water from the basin of NETCSS is allowed to enter 1st ETC through passage using pump resulting in the formation of closed loop. Also, water having enhanced temperature at the exit side of *N*th ETC is allowed to enter basin of NETCSS again and hence, T_{wo} will be same as T_{foN}. All unknown terms in equations (1) and (2) have been given in appendix of Singh and Tiwari [34].

3.2. EBEs for single slope solar still:

Following Singh et al. [5] and Tiwari et al. [6], the fundamental EBEs for various components of SS can be written. Further, these equations can be solved using Eqs. (1) and (2) to get water temperature (T_w), glass cover temperature at the inner surface (T_{gi}) and glass cover temperature at the outer surface (T_{go}) as follows:

$$T_w = \frac{\bar{f}(t)}{a}\left(1-e^{-at}\right)+T_{w0}e^{-at} \quad (3)$$

$$T_{gi} = \frac{\alpha'_g I_s(t)A_g + h_{1w}T_wA_b + U_{cga}T_aA_g}{U_{cga}A_g + h_{1w}A_b} \quad (4)$$

$$T_{go} = \frac{\frac{K_g}{L_g}T_{gi} + h_{1g}T_a}{\frac{K_g}{L_g}+h_{1g}} \quad (5)$$

The various unknown terms used in all the eqns. are given in the appendix of Singh and Tiwari [34]. After evaluating the values of T_w and T_{gi} from Eqs. (5) and (6) respectively, one can evaluate the value of hourly PW output as:

$$\dot{m}_{ew} = \frac{h_{ewg}A_b\left(T_w-T_{gi}\right)}{L'}\times 3{,}600 \quad (6)$$

Evaporative heat transfer coefficient (h_{ewg}) from the outer surface of water to the inner surface of glass cover can be computed as

$$h_{ewg} = 16.273\times10^{-3}h_{cwg}\left[\frac{P_w-P_{gi}}{T_w-T_{gi}}\right] \quad (7)$$

$$\text{Here, } h_{cwg} = 0.884\left[\left(T_w-T_{gi}\right)+\frac{\left(P_w-P_{gi}\right)\left(T_w+273\right)}{\left(268.9\times10^3-P_w\right)}\right] \quad (8)$$

$$P_w = \exp\left[25.317-\frac{5{,}144}{\left(T_w+273\right)}\right] \quad (9)$$

$$P_{gi} = \exp\left[25.317-\frac{5{,}144}{(T_{gi}+273)}\right] \quad (10)$$

Hourly thermal exergy for the solar distiller ($\dot{E}x_{thermal}(t)$) can be computed as follows [47]:

$$\dot{E}x_{thermal}(t) = A_b\times h_{ewg}\times\left[\left(T_w-T_{gi}\right)-\left(T_a+273\right)\times\ln\frac{\left(T_w+273\right)}{\left(T_{gi}+273\right)}\right] \quad (11)$$

The different terms used in Eqs. (4)–(12) have been presented in appendix of Singh and Tiwari [34]. The daily exergy can be evaluated by adding hourly exergy for 24 h using Eq. (12).

4. Sensitivity analysis for NETCSS

In general, the sensitivity analysis measures are the effect of some input variables on the output variables under some assumptions. The sensitivity analysis can be understood by the relationship between input and output parameters as shown in Fig. 3; it also provided a deep understanding of dependent and independent parameters, that is, inputs and outputs variables. The sensitivity can be quantized by sensitivity figure. Mathematically, the sensitivity figure can be expressed as follows:

$$\text{Sensitivity Figure} = \frac{\text{Percentage change in output parameter}}{\text{Percentage change in input parameter}} \quad (12)$$

The sensitivity analysis provides the information to the modeller that the system for which they want to design which parameters are critical ones followed by the other parameters [33]; this is the reason being involved with the sensitivity analysis, which provides it to the wide scope where the input and output variables involved. The sensitivity analysis results are very much appreciated; mathematically, it is defined as the ratio of change in output variables to change in input variables. Many sensitivity methods are available, and one of them is chosen for the present study because of its simplicity, most being used, and appreciable results. The selected sensitivity methods involve the effect on output parameters by changing the input variables/factors one at a time (OTA), while all the input variables kept constant. This process of changing input variables is repeated while keeping other constants until all the input variables/factors are being completed. Fig. 4 shows the schematic representation of the sensitivity analysis for the present study, which includes the different input and output parameters. Many input variables are there out of which effect of some input variables viz. wind velocity, ambient temperature, and solar flux intensity have not considered in this sensitivity analysis because these are the variables that are highly dependent on the weather conditions. The effect of others input variables have been studied and being computed, and plot have made for the corresponding input and output parameters.

5. Methodology

The sensitivity analysis has been gone through a standard step to step methodology for the projected distillation system having *N*-identical evacuated collectors which are couple in series and integrated with the single slope distillation unit.

- *Step-I:* Data like ambient air temperature and available solar irradiance have been taken from the Indian Metrological Department, Pune, India for the ambient conditions of New Delhi. Also, Liu and Jordan relation

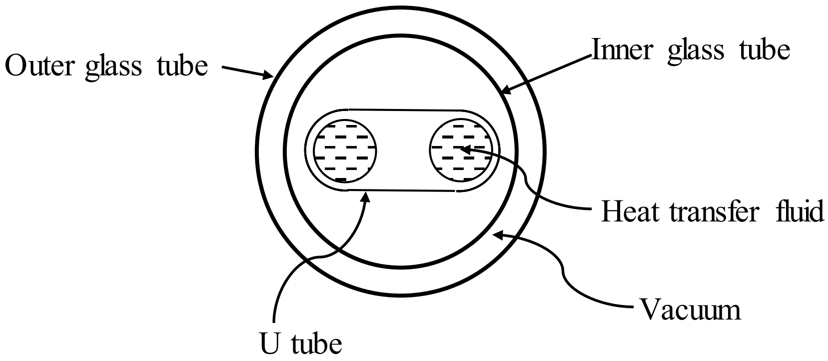

Fig. 2. Cross section side view of the first ETC.

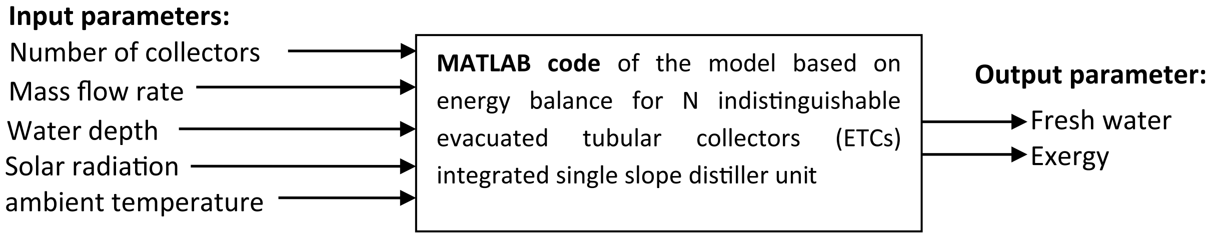

Fig. 3. Purification of saline/brackish water to potable water using ETCs integrated single slope solar desalination system.

has been used in the MATLAB-2015a to estimate solar intensity values at 30° northern latitudes for the inclined surface.

- *Step-II:* Primarily, values of T_w and T_{gi} have been estimated using Eqs. (3) and (4) in that order. Thereafter, the amount of hourly fresh water yielding has been estimated using Eq. (6) followed by the estimation of hourly exergy gain using Eq. (11). The summation of hourly values results in daily values of fresh water yielding and exergy gain.
- *Step-III:* Values of fresh water yielding as well as exergy gain has been estimated for the dissimilarity in one parameter at the input of system while all other parameters at the input of system are maintained constant.
- *Step-IV:* Then, repetition of Step-III has been done for all the considered input parameters. Each parameter has to be varied one at a time by keeping others constant excluding solar irradiance and ambient air temperature.
- *Step-V:* Then, corresponding percentage change on output has to be computed for each input variable by keeping others constant. In this way sensitivity figure for each variable can be obtained by the ratio of change in output to the corresponding change in input variable.
- *Step-VI:* Step-V has to be reiterated until the computation is not over for all the input variables. Hereafter, the obtained results have to be plotted on graphs.

The adopted methodology of sensitivity analysis can be better understood by the depicted flow chart in Fig. 4.

6. Results and discussion

All the relevant parameters at the input of active type solar still have been fed to the computer code written in MATLAB-2015a for performing sensitivity investigation of the system. Values of solar radiation and the surrounding temperature have been revealed as Fig. 5. They have been taken from IMD at Pune situated in India. The output received from the computer code has been revealed as Figs. 6–19. The sensitivity investigation in the present research work has been performed using OAT method of sensitivity analysis.

The dissimilarity in fresh water yielding with mass flow rate for NETCSS maintaining other input parameters as constant has been revealed as Fig. 6. It is observed from Fig. 6 that the value of daily fresh water yielding diminishes with the rise in value of mass flow rate due to improved quantity of water per unit time flowing through tubes of collector and hence the diminished increase in temperature is observed at the outlet of *N*th collector. It occurs because diminished energy absorption time is available for water flowing through tubes at increased mass flow rate. It is also observed from Fig. 6 that value of fresh water yielding becomes almost constant beyond certain value of mass flow rate and steady state is said to be achieved. At such state, heat absorption rate of water is approximately same as heat gained by absorber plate. Here, one should note that increased value of mass flow rate adversely affect fresh water yielding from the system.

The dissimilarity of percentage change in fresh water yielding with the percentage change in mass flow rate maintaining other input parameters as constant for NETCSS has been revealed as Fig. 7. The sensitivity figure of fresh water yielding with regard to mass flow rate can be obtained as slope of the curve shown in Fig. 6. It is clear from Fig. 7 that the sensitivity in fresh water yielding is higher at diminished values of mass flow rate and it tends to diminish at enhanced values of mass flow rate.

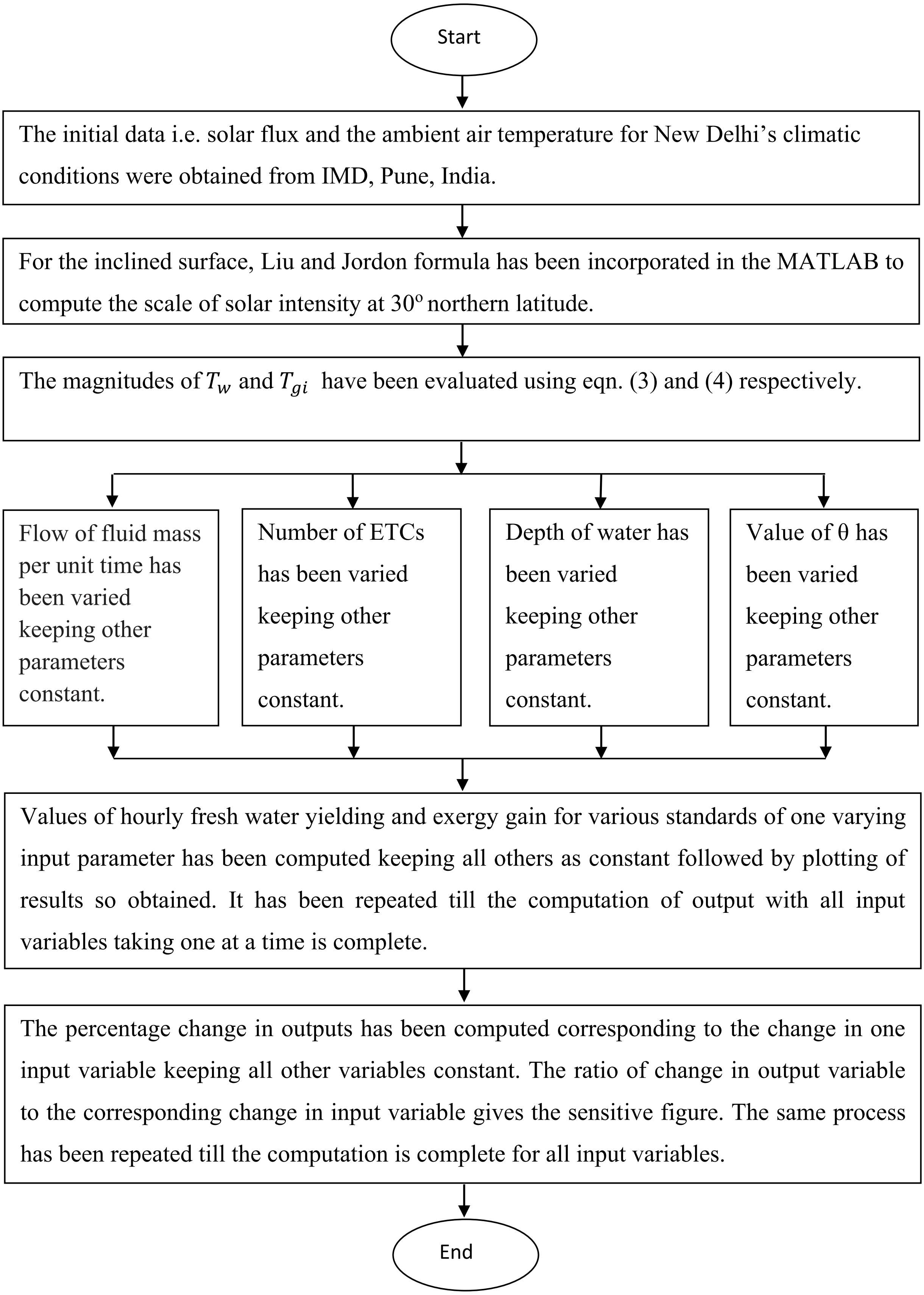

Fig. 4. Flow chart of methodology for carrying out sensitivity analysis for ETCs integrated single slope solar desalination system.

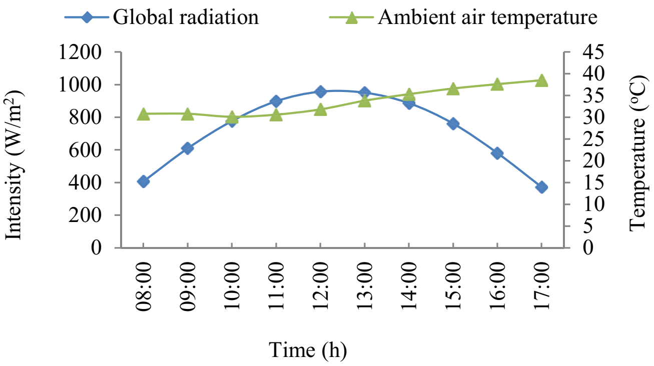

Fig. 5. Hourly variation of intensity and ambient air temperature for a typical day in the month of May.

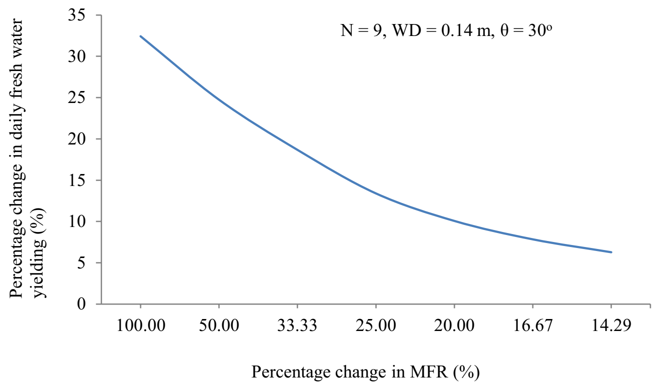

Fig. 7. Sensitivity of daily fresh water yielding with regard to MFR at selected values of N, θ and WD for NETCSS.

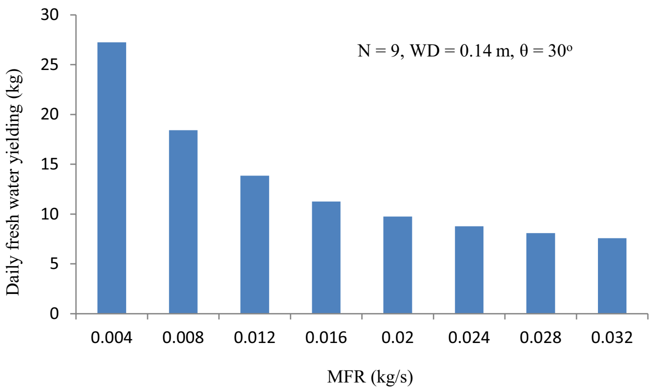

Fig. 6. Dissimilarity of daily fresh water yielding with MFR at selected values of N, collector inclination (θ) and WD for NETCSS.

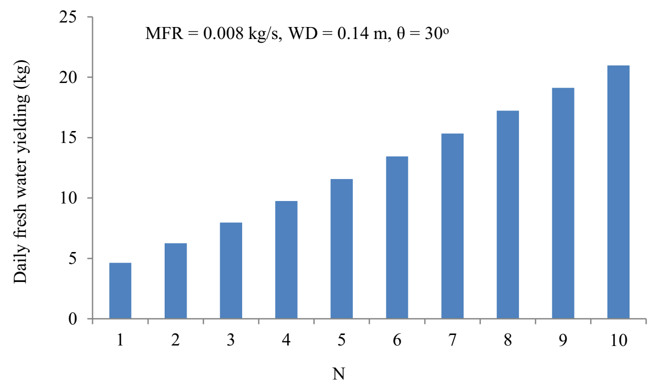

Fig. 8. Dissimilarity of daily PW yield with N at selected values of MFR, θ and WD for NETCSS.

It has been found to occur because of the fact that the percentage change in heat gain by N number of series connected collectors corresponding to the percentage change in mass flow rate at its diminished values is higher which further happens due to higher change in temperature.

The dissimilarity in fresh water yielding with N for NETCSS maintaining other input parameters as constant has been revealed as Fig. 8. It is clear from Fig. 8 that the value of fresh water yielding enhances with the enhanced value of N. It has been found to occur because of the fact that heat added to the water kept in basin also increases and with the increase in heat added to the water, the evaporation of water also increases, therefore with increase in the value of N higher magnitudes of fresh water yielding is obtained.

The dissimilarity of percentage change in fresh water yielding with the percentage change in N maintaining other input parameters as constant for NETCSS has been revealed as Fig. 9. The sensitivity figure of fresh water yielding with regard to N can be obtained as slope of the curve shown in Fig. 9. It is clear from Fig. 9 that the sensitivity in fresh water yielding is higher at diminished values of N and then the sensitivity tends to decrease at higher values of N. It has been found to happen due to the temperature difference between blackened surface of ETC and water flowing below the blackened surface is more at lower value of N and vice-versa. The area of each collector used for collecting heat is identical. It means the temperature of blackened surface of ETC is same for each ETC. However, the water/fluid coming from the basin and entering to inlet of collector will be having lower temperature at lower value of N. It results in the flowing of fluid at lower temperature below the blackened surface which further results in increased temperature difference between temperature of blackened surface and temperature of fluid which is responsible for increased heat transfer rate and ultimately amount of heat added is higher at lower values of N. Therefore, sensitivity in fresh water yielding comes out to be higher at diminished values of N.

The dissimilarity in fresh water yielding with water depth for NETCSS maintaining other input parameters as constant has been revealed as Fig. 10. It has been observed from Fig. 10 that daily fresh water yielding increases as water depth enhances. It has been found to occur because higher sensible heat is stored by water at increased water depth during day time as amount of water is more at enhanced water depth. This stored sensible heat is utilized during night, that is, off sunshine hours in the form of evaporation. With increased water depth, higher amount of sensible heat is stored during day time and this higher amount of stored sensible heat is released during off sunshine hours

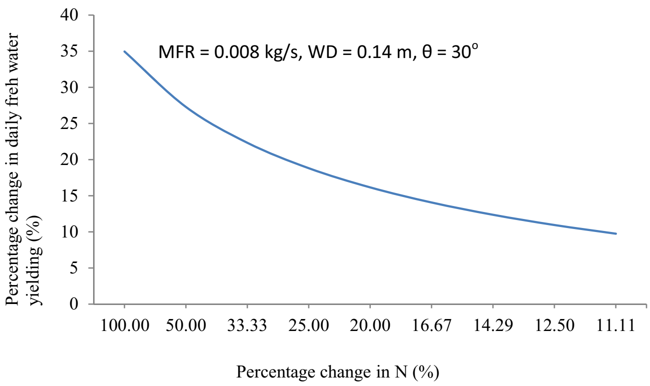

Fig. 9. Sensitivity of daily fresh water yielding with respect to N at selected values of MFR, θ and WD for NETCSS.

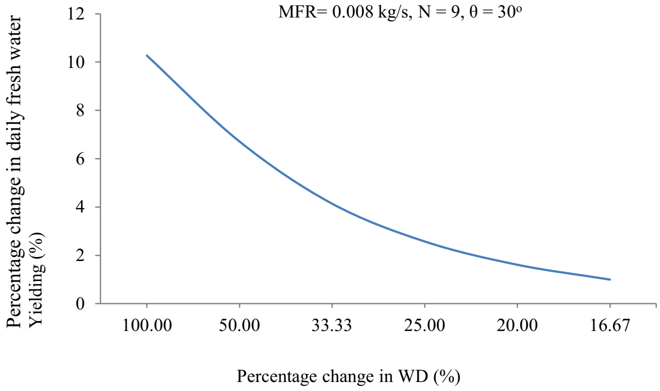

Fig. 11. Sensitivity of daily fresh water yielding with regard to WD at selected values of N, θ and MFR for NETCSS.

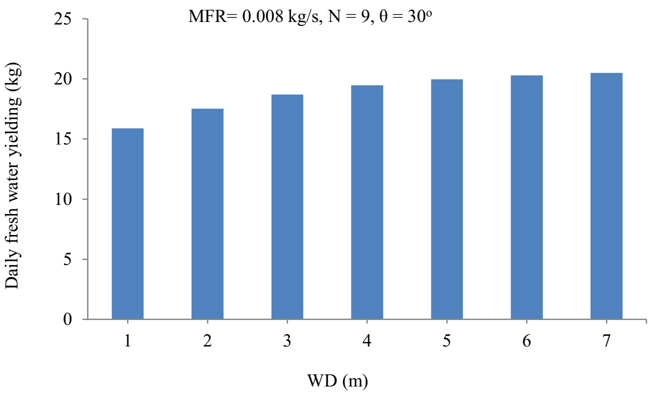

Fig. 10. Dissimilarity of daily fresh water yielding with WD at selected values of N, θ and MFR for NETCSS.

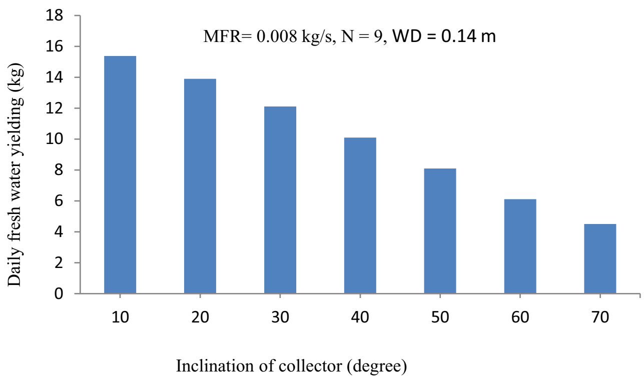

Fig. 12. Dissimilarity of daily fresh water yielding with θ at selected values of N, WD and MFR for NETCSS.

for the same amount of heat added. Hence, daily fresh water yielding increases with the increase in the value of WD.

The dissimilarity of percentage change in fresh water yielding with the percentage change in water depth maintaining other input parameters as constant for NETCSS has been revealed as Fig. 11. The sensitivity figure of fresh water yielding with regard to water depth can be obtained as slope of the curve shown in Fig. 11. It is clear from Fig. 11 that the sensitivity in daily fresh water yielding is higher at lower values of water depth and the sensitivity tends to decrease at higher values of water depth in basin. It has been found to occur due to higher rise in temperature of water in basin at lower water depth as water mass in basin is lesser. Hence, higher evaporation rate which results in higher change in PW yield.

The dissimilarity in fresh water yielding with collector inclination for NETCSS maintaining other input parameters as constant has been revealed as Fig. 12. It has been observed from Fig. 12 that daily fresh water yielding diminishes as collector inclination (θ) enhances. It has been found to occur because heat gain by collectors diminished at increased values of θ due to the fact that lesser solar energy is received by the collector surface. The dissimilarity of percentage change in fresh water yielding with the percentage change in θ maintaining other input parameters as constant for NETCSS has been revealed as Fig. 13. It is clear from Fig. 13 that decrease in percentage change is lesser for higher percentage change in θ at lower values of θ.

A comparison among sensitivities of daily fresh water yielding with regard to the percentage change in one parameter at the input of collector maintain other parameters at the input o system as constant has been revealed as Fig. 14. It is clear from Fig. 14 that fresh water yielding is most sensitive with regard θ followed by N, MFR and water depth. Therefore, designer should focus most on deciding value of θ while designing solar still of single slope type for getting fresh water for use on either individual level or industry level. The value of sensitivity figure can be computed using the slope of curve. The estimation of sensitivity figure has been revealed as Table 2. The mean values of sensitivity figures have been estimated to be 0.74, 0.66, 0.48 and 0.10 for θ, N, MFR and water depth in that order. It means that the collector inclination should be givn first priority followed by N, mass flow rate and water depth.

The dissimilarity in daily exergy gain with mass flow rate for NETCSS maintaining other input parameters as constant has been revealed as Fig. 15. It has been observed from Fig. 15 that the value of thermal exergy gain diminishes with the rise in value of mass flow rate due to improved quantity of water per unit time flowing through tubes of collector and hence the diminished increase in temperature is observed at the outlet of *N*th collector.

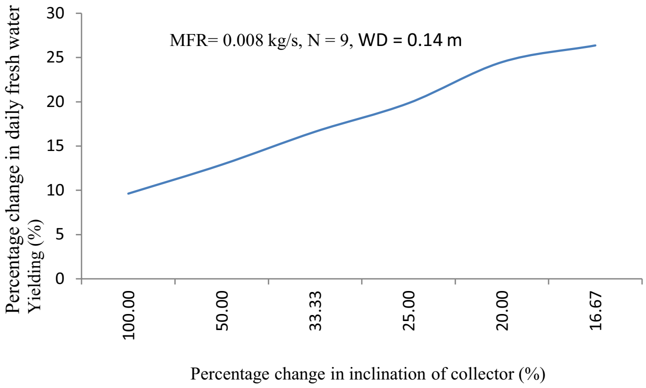

Fig. 13. Sensitivity of daily fresh water yielding with regard to θ at selected values of N, MFR and WD for NETCSS.

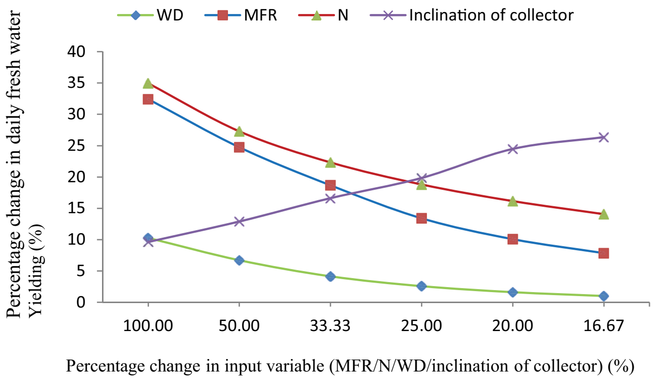

Fig. 14. Comparative sensitivity of PW yield with respect to input variable (MFR/N/WD/θ) for NETCSS.

Table 2
Computation of significant figure for fresh water (FW) from NETCSS

% change in input variable	% change in FW w.r.t. MFR	Sensitivity figure (SF) of FW w.r.t. MFR	% change in FW w.r.t. N	SF of FW w.r.t. N	% change in FW w.r.t. WD	SF of FW w.r.t. WD	% change in FW w.r.t. θ	SF of FW w.r.t. θ
100.00	32.43	0.32	34.95	0.35	10.27	0.10	9.63	0.10
50.00	24.74	0.49	27.28	0.55	6.71	0.13	12.89	0.26
33.33	18.67	0.56	22.32	0.67	4.14	0.12	16.62	0.50
25.00	13.40	0.54	18.80	0.75	2.57	0.10	19.85	0.79
20.00	10.07	0.50	16.15	0.81	1.61	0.08	24.48	1.22
16.67	7.84	0.47	14.06	0.84	1.00	0.06	26.37	1.58
	Average value of SF for (FW) w.r.t. MFR	0.48	Average value of SF for FW w.r.t. N	0.66	Average value of SF for FW w.r.t. WD	0.10	Average value of SF for FW w.r.t. θ	0.74

It occurs because diminished energy absorption time is available for water flowing through tubes at increased mass flow rate. It is also observed from Fig. 15 that value of exergy gain becomes almost constant beyond certain value of mass flow rate and steady state is said to be achieved. At such state, heat absorption rate of water is approximately same as heat gained by absorber plate. Here, one should note that increased value of mass flow rate adversely affect exergy gain from the system. The dissimilarity of percentage change in daily exergy gain with the percentage change in mass flow rate maintaining other input parameters as constant for NETCSS has been revealed as Fig. 16. The slope of this plot gives the sensitivity figure for PW yield with respect to MFR at selected values of other input parameters. It has been observed from Fig. 16 that the sensitivity in exergy gain is higher at lower values of MFR and the sensitivity tends to decrease at higher values of MFR. The reason being that the percentage change in exergy gain by N number of series connected collectors corresponding to the percentage change in MFR at its lower values is higher which happens due to higher change in temperature.

The dissimilarity in daily exergy gain with N for NETCSS maintaining other input parameters as constant has been revealed as Fig. 17. It is clear from Fig. 17 that the daily exergy gain enhances with the enhancement in value of N due to the fact that the solar energy collection area as well as exergy gain of collector enhances with the enhancement in value of N. The dissimilarity of percentage change in daily exergy gain with the percentage change in N maintaining other input parameters as constant for NETCSS has been revealed as Fig. 18. The slope of this plot gives the sensitivity figure for daily exergy with respect to N at selected values of other input parameters. It is clear from Fig. 18 that the sensitivity in exergy gain by the system is higher at diminished values of N and then the sensitivity tends to decrease at higher values of N. It has been found to happen due to the temperature difference between blackened surface of ETC and water flowing below the blackened surface is more at lower value of N and vice-versa. The area of each collector used for collecting solar energy as well as exergy is identical. It means the temperature of blackened surface of ETC is same for each ETC. However, the water/fluid coming from the basin and entering to inlet of collector will be having lower temperature at lower value of N. It results in the flowing of fluid at lower temperature below the blackened surface which further results in increased temperature

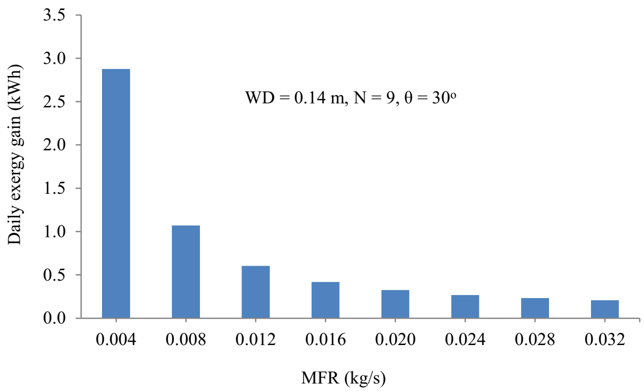

Fig. 15. Dissimilarity of daily exergy gain with MFR at selected values of N, θ and WD for NETCSS.

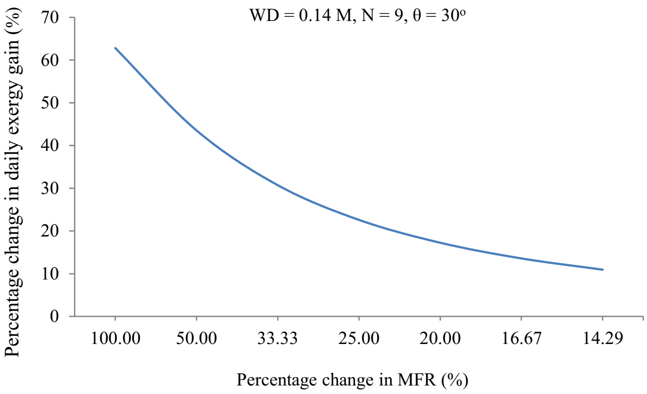

Fig. 16. Sensitivity of daily exergy gain with regard to MFR at selected values of N, θ and WD for NETCSS.

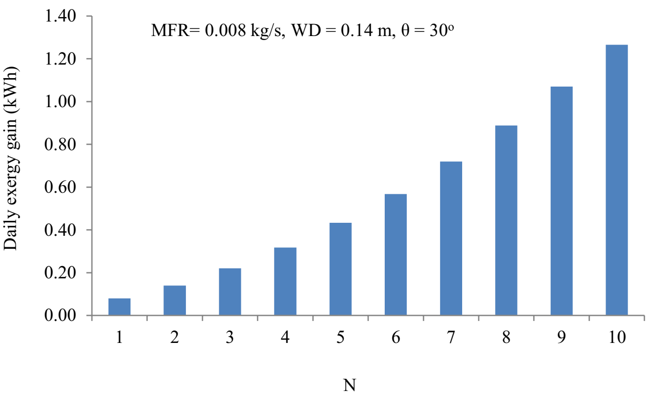

Fig. 17. Dissimilarity of daily exergy gain with regard to N at selected values of MFR, θ and WD for NETCSS.

difference between temperature of blackened surface and temperature of fluid which is responsible for increased exergy transfer rate and ultimately amount of heat added is higher at lower values of N. Therefore, sensitivity in exergy gain comes out to be higher at diminished values of N.

The dissimilarity in daily exergy gain with water depth for NETCSS maintaining other input parameters as constant has been revealed as Fig. 19. It is clear from

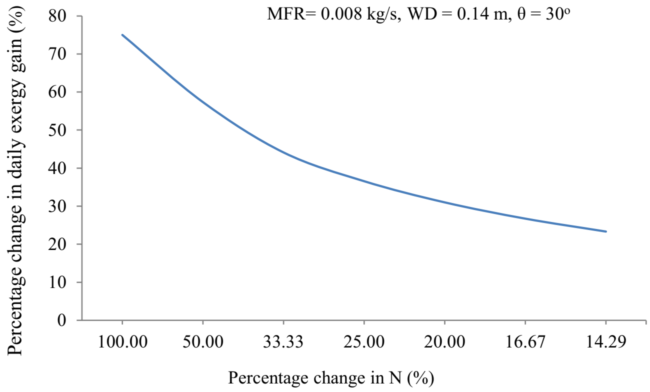

Fig. 18. Sensitivity of daily exergy gain with regard to N at selected values of MFR, θ and WD for NETCSS.

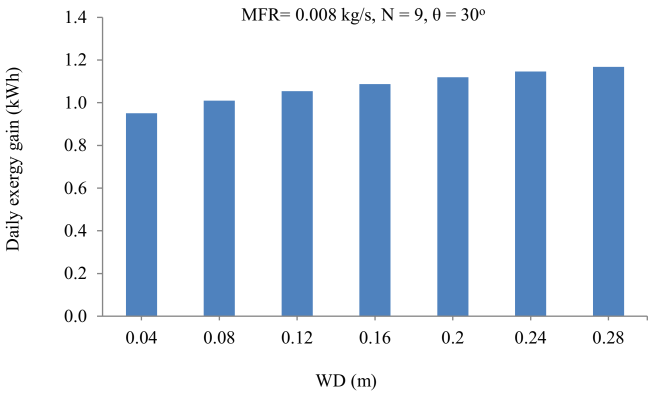

Fig. 19. Dissimilarity of daily exergy gain with WD at selected values of MFR, θ and N for NETCSS.

Fig. 19 that the daily exergy gain enhances with the enhancement in the value of water depth. At higher value of water depth, two reverse phenomena seem to occur. During sunshine hours, exergy gain by the system diminishes with the enhancement in the value of WD due to the fact that diminished temperature is obtained with enhanced values of WD because storage of heat in water mass occurs as sensible heat. However, this stored sensible heat is made use of during off sunshine hours and comparatively enhanced temperature is obtained during night time. Hence, exergy gain by the system enhances with the in enhancement in the value of water depth during night time and this increased exergy gain by the system overcome the diminished exergy during day time. Therefore, daily exergy gain by the system which is the addition of exergy gain during day time as well as exergy gain by the system during night time enhances with the enhancement in the value of WD. The percentage change in daily exergy gain with percentage change in water depth at selected values of mass flow rate, collector inclination and N has been revealed as Fig. 20. It is clear from Fig. 20 that the sensitivity is initially higher and it decreases at the percentage change in WD decreases due to similar variation in sensible heat in water mass.

The dissimilarity in thermal exergy gain with collector inclination for NETCSS maintaining other input parameters as constant has been revealed as Fig. 21. It has been observed from Fig. 21 that daily thermal exergy gain diminishes as collector inclination (θ) enhances. It has been found to occur because exergy gain by collectors diminished at increased values of θ due to the fact that lesser solar energy/solar exergy is received by the collector surface. The dissimilarity of percentage change in thermal exergy gain with the percentage change in θ maintaining other input parameters as constant for NETCSS has been revealed as Fig. 22. It is clear from Fig. 22 that decrease in percentage change is lesser for higher percentage change in θ at lower values of θ. The slope of this curve will give the value of sensitivity figure.

A comparison among sensitivities of daily thermal exergy gain with regard to the percentage change in one parameter at the input of collector maintaining other parameters at the input to system as constant has been revealed as Fig. 23. It is clear from Fig. 23 that the thermal exergy gain is most sensitive with regard N followed by θ, mass flow arte and water depth. Therefore, designer should focus most on deciding value of N while designing solar still of single slope type for getting thermal exergy gain. The value of sensitivity figure can be computed using the slope of curve. The estimation of sensitivity figure has been revealed as Table 3. The mean values of sensitivity figures have been estimated to be 1.31, 1.21, 0.83 and 0.10 for N, θ, mass flow rate and water depth respectively. It means that the N should be given first priority followed

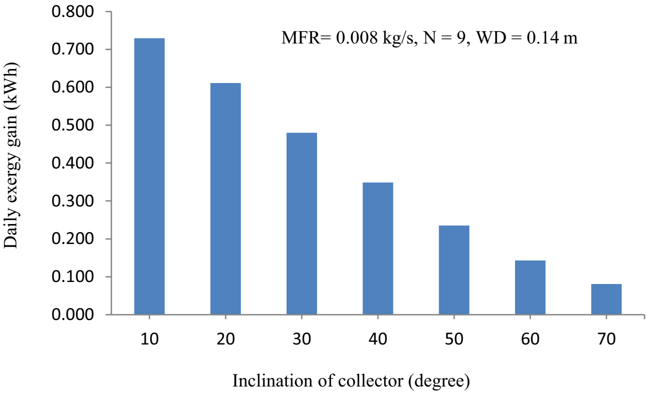

Fig. 21. Dissimilarity of daily exergy gain with N at selected values of MFR, θ and WD for NETCSS.

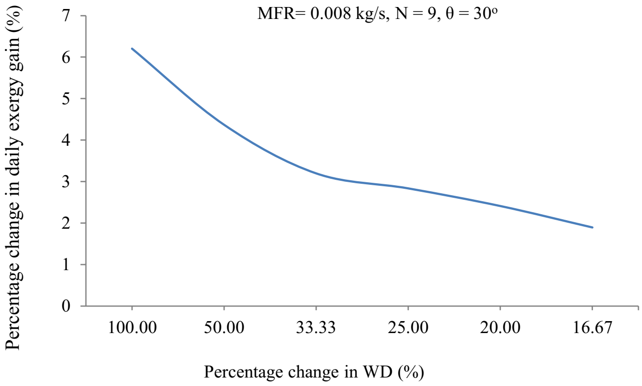

Fig. 20. Sensitivity of daily exergy gain with regard to WD at selected values of MFR, θ and N for NETCSS.

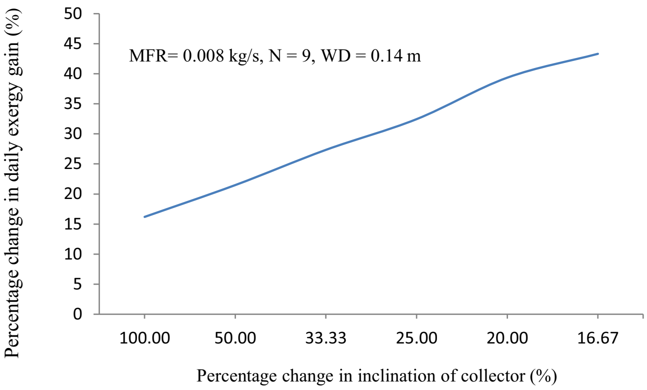

Fig. 22. Sensitivity of daily exergy gain with regard to inclination of collector at selected values of MFR, WD and N for NETCSS.

Table 3
Computation of significant figure for exergy from NETCSS

% change in input variable	% change in exergy w.r.t MFR	Sensitivity figure (SF) of exergy w.r.t. MFR	% change in exergy w.r.t. N	SF of exergy w.r.t. N	% change in exergy w.r.t WD	SF of exergy w.r.t. WD	% change in exergy w.r.t θ	SF of exergy w.r.t. θ
100.00	62.80	0.63	75.00	0.75	6.20	0.06	16.19487	0.16
50.00	43.53	0.87	57.34	1.15	4.37	0.09	21.48508	0.43
33.33	30.72	0.92	44.12	1.32	3.20	0.10	27.34163	0.82
25.00	22.60	0.90	36.56	1.46	2.84	0.11	32.44643	1.30
20.00	17.25	0.86	31.00	1.55	2.41	0.12	39.33977	1.97
16.67	13.57	0.81	26.72	1.60	1.90	0.11	43.30581	2.60
	Average value of SF for exergy w.r.t. MFR	0.83	Average value of SF for exergy w.r.t. N	1.31	Average value of SF for exergy w.r.t. WD	0.10	Average value of SF for exergy w.r.t. θ	1.21

Table 4
Limits of input parameters that affect the output of single slope solar still integrated with N identical evacuated tubular collectors (NETCSS)

Variable	Range	Remarks
N (Number of collectors)	1–10	Value of fresh water yielding has been found increasing as the value of N is enhanced. However, increase in N results in the enhancements of both initial investment as well as water temperature. Hence, it is recommended to keep in mind the boiling point of water and initial investment while deciding the value of N. Temperature of water should be less than its boiling point. Also, the revenue obtained by selling PW should justify the initial investment.
Mass flow rate (MFR)	0.004–0.032 kg/s	The value of fresh water yielding as well as exergy has been found to diminish with the enhancement in the value of MFR. Also, one need to keep in mind that water temperature in the basin should not go beyond above its boiling point. The recommended value of MFR is 0.04 kg/s.
Depth of water in the basin (WD)	0.04–0.28 m	Value fresh water yielding gets enhanced with the enhancement in the value of water depth. Value of PW increases due to the utilization of sensible heat at night collected during the sunshine hours. Hence, higher values of depth of water are recommended.
Inclination of collector (θ)	10°–15°	The value of fresh water yielding as well as thermal exergy gain diminishes as the value of θ increases due to lower gain of collector at enhanced values of θ because of lower solar energy received by the collector surface. So, lower value of θ is recommended for summer season.

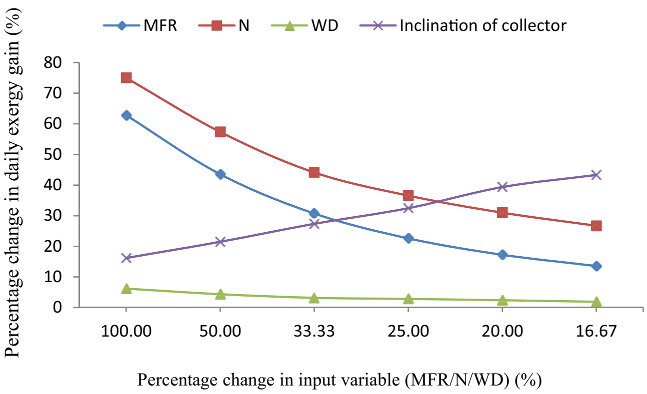

Fig. 23. Comparative sensitivity of daily exergy with respect to input variables (MFR/N/WD/θ).

by θ, mass flow rate and water depth. Table 4 summarizes limits of input parameters that affect the output of solar still of single slope type included with N similar evacuated tubular collectors having series connection.

7. Conclusions

Solar still of single slope type included with N similar evacuated tubular collectors having series connection has been studied in this work and sensitivity analysis accomplished for the same. On the basis of research outcomes, the subsequent conclusions have been transcribed as:

- The value of fresh water yielding and daily exergy gain from the system have been found to diminish by increasing mass flow rate for a constant water depth, collector inclination and N. However, the increase in the number of N leads to raise the values of fresh water yielding as well as daily exergy gain maintaining other parameters at input of the system as constant. However, the temperature of fluid/water should be less than its boiling point while deciding value of N during design and installation phases.
- The fresh water yielding on hourly basis and daily exergy gain have been found increasing with rise in water depth maintaining all other parameters at the input of system constant. Hence, higher value of water depth should be adopted.
- The fresh water yielding on hourly basis and daily exergy gain have been found diminishing with rise in collector inclination keeping all other parameters at the input of system constant. Hence, lower values of collector inclination should be preferred.
- The sensitivity investigation of NETCSS indicates that the fresh water yielding is most sensitive with regard to θ followed by N, mass flow rate and water depth; whereas, exergy gain is most sensitive with regard to N followed by θ, mass flow rate and water depth
- The mean sensitivity figure values for fresh water yielding comes out to be 0.74, 0.66, 0.48 and 0.10 corresponding to θ, N, mass flow rate and water depth respectively. Whereas, the mean sensitivity figure values for daily exergy gain has been obtained as 1.31, 1.21, 0.83 and 0.10 corresponding to N, θ, mass flow rate and water depth respectively.

Symbols

A_b	—	Area of basin, m^2
A_g	—	Area of glass cover, m^2
C	—	Specific heat capacity, J/kg-K
SS	—	Single slope solar still
F'	—	Collector efficiency factor, dimensionless
ETC	—	Evacuated tubular collector
HTC	—	Heat transfer coefficient

h_{cwg}	—	Convective HTC from water to inner surface of glass cover, W/m²-K
h_{ewg}	—	Evaporative HTC from water surface to inner surface of glass cover, W/m²-K
h_{ba}	—	HTC from blackened surface to water mass, W/m²-K
h_{bw}	—	HTC from blackened surface to water mass, W/m²-K
h_{rwg}	—	Radiative HTC from water surface to inner surface of glass cover, W/m²-K
h_r	—	Radiative HTC, W/m²-K
h_{1w}	—	Total HTC from water surface to inner surface of glass cover, W/m²-K
h_{1g}	—	Total HTC from outer surface of glass cover facing to ambient, W/m²-K
$I(t)$	—	Solar intensity on collector, W/m²
$I_S(t)$	—	Solar intensity on glass cover of solar still, W/m²
K	—	Thermal conductivity, W/m-K
L_g	—	Thickness of glass, m
L	—	Latent heat, J/kg
L'	—	Length, m
MFR/$\dot{m}_f$	—	Mass flow rate of fluid/water, kg/s
$\dot{m}_{ew}$	—	Mass of distillate per hour from *N*-ETC-DS, kg
N	—	Number of collectors
NETCSS	—	Solar still of SS type included with N similar ETCs having series connection
PF_c	—	Penalty factor due to the glass covers for the glazed portion
PF_1	—	Penalty factor first, dimensionless
PF_2	—	Penalty factor second, dimensionless
PW	—	Potable water
SA	—	Sensitivity analysis
SF	—	Sensitivity figure
T_{foN}	—	Outlet water temperature at the end of *N*th water collector, °C
T_a	—	Ambient air temperature, °C
T_{gi}	—	Glass temperature at inner surface of glass cover, °C
t	—	Time, h
T_{w0}	–	Water temperature at $t = 0$, °C
T_w	–	Water temperature, °C
U_L	—	Overall heat transfer coefficient
V	—	Velocity of air, m/s
WD	—	Water depth

Subscript

eff	—	Effective
ex	—	Exergy
f	—	Fluid
g	—	Glass
in	—	Incoming
out	—	Outgoing
w	—	Water

Greek

α	—	Absorptivity (fraction)
η	—	Efficiency, %
$(\alpha\tau)_{eff}$	—	Product of effective absorptivity and transmittivity
σ	—	Stefan–Boltzmann constant, W/m²-K⁴
τ	—	Transmittivity
θ	—	Collector inclination

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