Thermal Model and Performance Analysis of PVT Non-metallic Solar Water Heater

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ABSTRACT

In the present paper, a photovoltaic thermal (PVT) non-metallic solar water heater (PVNMSWH) made of modified solar collector and glass-to glass PV module, is simulated on MATLAB and validated with the experiments performed in the month of April and December, 2017. The modified solar water heater is made of Fibre-reinforced plastic (FRP) and acrylic with an aim to develop a corrosion resistant and economical system by using the thermally insulating materials which eliminates the use of insulation for the domestic use. The experimental setup is installed at the M.N.N.I.T. Allahabad, Allahabad, U.P India (latitude $25^{\circ} 27'N$ and longitude $81^{\circ} 44'$). The maximum water temperature in the tank is found to be $65.6^{\circ}C$ and $40.0^{\circ}C$ in the month of April and December, 2017 respectively. Maximum thermal efficiencies have been found to be 43.9% and 38.3% in the month of April and December respectively at 13:00hr and electrical efficiency is found to vary between 11-12.5%. The enviro-economic analysis and energy matrices is also carried out and the carbon mitigation cost is obtained as Rs. 1915 per annum.

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1. Introduction

Photovoltaic thermal (PVT) systems are the solar devices that produces electricity and heat simultaneously using solar energy (GN Tiwari, 2013). These systems are the integration of solar collector and PV module. Integration of solar devices into one reduces the heat loss. The main concept of these systems were first introduced by Kern and Russel (1978). Raghuraman (1981) studied the thermal performance of PVT flat plate collector using numerical methods. Later many researchers analyzed the PVT system (Garg et al., 1994; Zondag et al., 2002; Chow, 2003; Zakharchenko et al., 2004). Kalogirou (2001) observed the monthly behaviour of hybrid PVT system (unglazed) for the climatic conditions of Cyprus and operating in forced convection mode and reported that the mean annual PV efficiency increases from 2.8 to 7.7% with a thermal efficiency of 49%. Sandnes and Rekstad (2002) studied the performance of a PVT module made by pasting mono-crystalline silicon solar cells onto a black plastic solar heat absorber (unglazed) PVT system. Dubey and Tiwari (2008) stated that energy payback period can be reduced by increasing the overall efficiency of these systems. Hasan et al. (2018) designed a PVT solar collector using the concept of water jet collision. The solar intensity was varied (using solar simulator) from 500 to 1000 W/m^2 and mass flow rate from 0.033 to 0.16 kg/s. Hasan reported that the mass flow rate have direct relation with the overall efficiency the system irrespective of the solar radiation. Tiwari et al. (2009) obtained an

analytical expression for the water temperature of an integrated PVT solar water heater under constant flow rate hot water withdrawal. Analysis is based on basic energy balance for hybrid flat plate collector and storage tank respectively. The analysis is extended for hot water withdrawal at constant collection temperature. Thermal efficiency of IPVTS increases with increased constant flow rate and decreases with an increase in constant collection temperature. Efficiency is maximum at hot water withdrawal flow rate of 0.006kg/s. Thus precocious progress has been made in research of PVT collectors so far since integration of PV module with the thermal collector reduces the water temperature and hence results in lower temperature difference between ambient and water temperature, utilizing that amount of heat to produce electricity. Reduced temperature difference between ambient temperature and water temperature inside the collector leads to lower losses (Dev and Tiwari, 2011).

It can be observed from the these literatures that in the recent past (a) the focus has been made to increase the efficiency and reduce the losses by using hybrid systems or integrated systems which provides hot water along with the electricity from a single unit, saving floor area requirement for separate production of electricity and hot water, since increasing population and limited land, forces the researchers and engineers to progress toward portability in addition of better efficiency and reduced losses. (b) Integration of conventional water heaters i.e. flat plate collector (FPC) &

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evacuated tube collector (ETC) with PV modules of different types have been keenly focused and analyzed while integration of modified systems with PV modules has been neglected. (c) These days thermally insulating materials are also being employed with an aim to reduce the losses and to increase the portability of the systems so as to make it attractive for domestic use. Recently Tewari and Dev (2018) studied the performance of modified solar water heater made of FRP-acrylic (thermally insulating materials) storage tank and collector with metal absorber plate. Later Tewari and Dev (2019) integrated the modified system with the PV module and carried out experiment with the PVT system made of purely non-metallic materials- FRP, thermocol and acrylic. In collector, the tubes were insulated at the bottom with the FRP-thermocol-FRP assembly. In the present paper, the assembly of FRP-thermocol has been removed from the bottom of the tubes in the collector since tubes are made of thermally insulating material (acrylic) which is a good resistor of heat (thermal conductivity of acrylic is 0.2 W/mK) and its performance has been studied to analyze the effect of removing the insulation from the collector. This modification has been done with a view to avoid wastage of materials used in the system and make it lighter and portable for domestic use.

Fig. 1 :Schematic diagram of (a) solar collector
(b) PVT non-metallic solar water heater

2. Experimental Setup

Fig. 1 shows a schematic diagram of the components of the non-metallic solar water heater i.e. solar collector and storage tank. The solar collector is made of 10 thermally insulating material tubes (methyl methacrylate commonly known as acrylic) and these tubes are surrounded by the semi-circular tubes of same material on the upper half while the lower half is simply supported by a light support. The inner half of the inner tubes are coated with the SnS-Cu_xS which is an absorptive coating material having absorptance of 0.91 (Tse and Chow, 2002). Space between the adjacent tubes of the collector has been reduced than the conventional designs (FPC, ETC) which results in the 43% lower collector area than conventional systems. The total collector area is 0.61m² and length of each tube is 1m. The collector is connected to the trapezoidal water storage tank of 100L at an angle of 25° (as per latitude of Allahabad) and the basin and north wall of the storage tank is made of black painted FRP

to absorb the maximum amount of solar radiations. The rest of the walls of the storage tank is made of double layered acrylic sheets. Double layered walls reduces the heat loss from the storage tank to the surrounding during off-sunshine hours. Various design and operational parameters of solar collector is shown in Table 1 and the advantages of the design are listed below:

Table 1: Various design parameters of PVTNMSWH

Specifications	Dimensions	Specifications	Dimensions
α_{ct}	0.9	ρ_w	1000 kg/m ³
α_{FRP}	0.9	L	1m
α_w	0.6	A_c	1.6m ²
α_{acry}	0.05	K_{acry}	0.2 W/m K
τ_{acry}	0.92	r_1	0.01m
τ_w	0.35	r_c	0.009m
h_i	2.55 W/m ² K	r_2	0.0125m
N_t	10	r_3	0.022m
$\dot{m}$	0.02 kg/s	r_4	0.025m
$V_{1\text{ tube}}$	0.000314 m ³	$\dot{m}_w$	0.02 kg/s
V_T	100 L	M_{TW}	194.973 kg
M_{tw}	5.026 kg	K_{FRP}	0.0351 W/mK
t_{FRPi}	0.0438m	h_w	200 W/m ² K
t_{acryt}	0.003m	t_{FRPT}	0.005 m
A_S	0.355 m ²	A_E	0.238 m ²
A_W	0.238 m ²	A_b	0.355 m ²
A_{top}	0.391 m ²	Space b/w tubes	0.0095 m
h_{bw}, h_{nw}	500	K_{ct}	0.5 W/m K

Advantages:

- Convective losses inherent in FPC get reduced because of the use of evacuated tubes and vacuum between sheets of acrylic in the storage tank reduces losses during off sunshine hours and allows solar radiation to heat water during sunshine hours.
- In the present system, only non-metals have been used which reduces the cost associated with metals in earlier systems and make system corrosion free.
- Acrylic is light material and hence the water heating system becomes lighter than conventional system. Thus easy in transportation. Transmittance of acrylic is very high (92%) and conductivity is low. Thus increased input solar radiation.
- Proper utilization of incident solar radiation due to reduced gaps between tubes and no shading effect as the tubes are transparent (Tewari and Dev, 2018)
- Circular tubes increases the solar exposure period of the heater from early morning till evening.
- Use of acrylic instead of metal further cut off the conduction of heat to the outside environment and thus provides insulation.

A glass-to-glass PV module of 75 watt is installed at the top surface of the storage tank to produce electricity in addition of hot water and connected to a load. The specifications of the solar module is listed in Table 2. PV module is installed at the top surface with a small air gap which act as an insulation between hot water and PV module. Also, the installation of the PV module reduced the movement of air above top layer of storage tank and hence reduces loss of heat which get increased during off-sunshine hours due to the temperature difference between water and ambient temperature. Thus, the system serves as PVT system (Tewari and Dev, 2019) and works on density difference (thermosiphon system) same as conventional systems with little modification. Initial heating of water begins in the collector as solar radiations falls on it. Hot water

Table 2. Electrical parameters of Glass-to-glass PV module

Electrical Parameters	Values/Specifications
Solar cell type	polycrystalline type
Solar cell size	0.0047 m ²
Maximum Power	75Wp
Area of module	0.233m ²
No. of cell	36
Packing factor	0.72

(having lower density) moves upward toward storage tank and water from the storage tank (higher density) fill the space in the tube. Hot water, even after reaching the storage tank continues to collect the heat from the solar radiation penetrating inside the transparent storage tank. Thus, water get heated by the combined effect of solar collector and storage tank.

3. Instrumentation

For the measurement of the temperature of water, copper constantan type-T thermocouples in combination with the calibrated temperature scanner (CHUWDHARY PRODUCTS DTA 10) were used at the three different heights of north wall in storage tank and at the ends of the collector tubes. Solar radiation falling at various surfaces of the water heater were measured using the AMPROBE (Model SOLAR-100) solar power meter. Wind velocity and ambient temperatures were recorded using Anemometer (FLUKE Model BTH401).

4. Thermal Modeling

The thermal model is the language of expressing the thermal processes taking place in the system with the help of energy balance equations. Energy balance equation relates the input energy with the output energy for each component which is further solved to obtain final desired temperatures of water and different surfaces. The energy balance for each component of the PVNMSWH has been carried out with the following assumptions to understand the flow of heat taking place in the collector and storage tank,

- The setup is completely water and vapour leakage proof.
 - The heat capacities of coating, FRP, acrylic are negligible.
 - System operates in quasi-steady state regime during the day.
 - The temperature of coating and FRP base are considered to be uniform.
- The reference for PV cell and nomenclature for water heater are taken from Dubey and Tiwari (2008) and Tewari and Dev(2016) respectively.

4.1. A. For solar cells of PV module (glass-glass):

Incident energy absorbed by solar cells = heat convected to atmosphere + energy converted into electricity

$$\alpha_c \tau_c \beta_c I_{top}(t) W dx = [U_{tc,a} (T_c - T_a) + \eta_c \tau_c \beta_c I_{top}(t)] W dx \quad (1)$$

From above equation cell temperature is given by

$$T_c = \frac{(\alpha \tau)_{eff} I_{top}(t) + U_{tc,a} T_a}{U_{tc,a}} \quad (2)$$

3.5.2 Modeling of collector

1. For Coating:

Heat absorbed by coating = heat convected to water + heat given to ambient.

$$\alpha_{ct} (\tau_{acry}^2 \tau_w I_t(t)) A_c = h_w A_c (T_{ct} - T_{hw}) + U_{1d3} A_c (T_{ct} - T_a) \quad (3)$$

$$T_{ct} = \frac{\alpha_{ct} [\tau_{acry}^2 \tau_w I_t(t)] + h_w T_{hw} + T_a U_{1d3}}{h_w + U_{1d3}} \quad (4)$$

2. For water in tube:

Heat absorbed by water + heat convected to water from coating = energy stored by water + heat transfer from hot water to cold water + heat given to ambient.

$$\alpha_w [\tau_{acry}^2 \tau_w I_t(t)] \frac{A_w}{2} + h_w A_c (T_{ct} - T_{hw}) = M_w C_w \frac{dT_{hw}}{dt} + \dot{m}_w C_w (T_{hw} - T_{cw}) + U_{2d3} A_w (T_{hw} - T_a) \quad (5)$$

3. For inner surface of inner tube:

Heat convected from water to tube + heat convected to inner surface from coating = heat given to ambient.

$$h_w \frac{A_{it}}{2} N_i (T_{hw} - T_{ii}) + h_{ct} A_c (T_{ct} - T_{ii}) = N_i A_{it} (T_{ii} - T_a) U_{3d3} \quad (6)$$

$$T_{ii} = \frac{h_w \frac{A_{it}}{2} T_{hw} + h_{ct} A_c T_{ct} + T_a A_{it} U_{3d3}}{A_{it} U_{3d3} + h_{ct} A_c + \frac{A_{it}}{2} h_w} \quad (7)$$

4. For outer surface of inner tube:

Heat convected from inner tube surface to outer surface of outer tube = heat convected from outer surface to ambient.

$$h_{oi} (T_{ii} - T_{io}) = U_{4d3} (T_{io} - T_a) \quad (8)$$

$$T_{io} = \frac{T_{ii} h_{oi} + T_a U_{4d3}}{h_{oi} + U_{4d3}} \quad (9)$$

5. For inner surface of outer tube:

Heat convected from outer surface of inner tube to inner surface of outer tube = heat convected from inner surface of outer tube to ambient.

$$h_i \frac{A_{oi}}{2} (T_{io} - T_{oi}) = U_{5d3} A_{oi} (T_{oi} - T_a) \quad (10)$$

$$T_{oi} = \frac{U_{5d3} A_{oi} T_a + h_i T_{io} \frac{A_{oi}}{2}}{U_{5d3} A_{oi} + h_i \frac{A_{oi}}{2}} \quad (11)$$

6. For outer surface of outer tube:

Heat convected from inner surface of outer tube to outer surface of outer tube = heat convected from outer surface of outer tube to ambient

$$h_{o2} A_{oot} (T_{oi} - T_{oo}) = h_o A_{oot} (T_{oo} - T_a) \quad (12)$$

$$T_{oo} = \frac{T_{oi} h_{o2} + T_a h_o}{h_{o2} + h_o} \quad (13)$$

Putting the value of T_a in Equation 5 we obtain,

$$\frac{dT_{hw}}{dt} + a_1 T_{hw} + b_1 T_{cw} = g_1(t) \quad (14)$$

C. For tank section

1. For water in storage tank

Rate of heat supplied = rate of heat absorbed + rate of heat rejected

$$\alpha_e [I_e(t) A_e + I_{tr}(t) A_{tr}] \tau_{acry}^2 + \alpha_w [I_e(t) A_e + I_{tr}(t) A_{tr}] \tau_{acry}^2 + h_w A_e (T_{ei} - T_{ew}) + h_w A_{tr} (T_{ei} - T_{ew}) + \dot{m}_w C_w (T_{ew} - T_{cw}) = M_w C_w \frac{dT_{cw}}{dt} + h_{tw} A_e (T_{cw} - T_{wi}) + h_{tw} A_{tr} (T_{cw} - T_{wi}) + h_{tw} A_e (T_{cw} - T_{wi}) + h_{tw} A_{tr} (T_{cw} - T_{wi}) \quad (15)$$

2. For east wall (inner surface of inner layer)

Heat absorbed from radiation + heat gained from water = heat lost to the outer surface of east wall

$$\alpha_{acry} [I_e(t) A_e] \tau_{acry} + h_{tw} A_e (T_{cw} - T_{Eii}) = \frac{K_{acry} A_e (T_{Eii} - T_{Eio})}{t_{acry}} \quad (16)$$

3. For east wall (outer surface of inner layer)

$$h_{kacry} A_e (T_{Eii} - T_{Eio}) = h_i A_e (T_{Eio} - T_{Eoi}) \quad (17)$$

4. For east wall (inner surface of outer layer)

$$h_i A_e (T_{Eio} - T_{Eoi}) = h_{kacry} A_e (T_{Eoi} - T_{Eoo}) \quad (18)$$

5. For east wall (outer surface of outer layer)

$$h_{kacry} A_e (T_{Eoi} - T_{Eoo}) = h_o A_e (T_{Eoo} - T_a) \quad (19)$$

6. For north wall (inner surface)

$$\alpha_{FRP} I_V(t) A_N \tau_{acry}^2 \tau_w = h_{NW} A_N (T_{Ni} - T_{cw}) + \frac{K_{FRP} A_N (T_{Ni} - T_{No})}{t_{FRPT}} \quad (20)$$

7. For north wall (outer surface)

$$h_{kFRP} A_N (T_{Ni} - T_{No}) = h_o A_N (T_{No} - T_a) \quad (21)$$

By putting the values of T_{Eii} , T_{Eio} , T_{Eoi} , T_{Eoo} , T_{Eii} & T_{Ni} in (10) and get

$$\frac{dT_{cw}}{dt} + a_2 T_{hw} + b_2 T_{cw} = g_2(t) \quad (22)$$

Adding (14) and (22) (after multiplying (22) by β) and solving (after multiplying by $e^{\alpha t}$) further to get,

$$\frac{d}{dt} (e^{\alpha t} (T_{hw} + \beta T_{cw})) = \{g_1(t) + \beta g_2(t)\} e^{\alpha t} \quad (23)$$

Further, some assumptions have been made for solving (19),

- small time interval dt ($0 < t < dt$)
- function $f(t)$ are constant, i.e., $f(t) = \overline{f(t)}$ for small interval dt .
- a is a constant during the time interval
- Initial values of hot water and cold water temperatures have been used to determine value of internal heat transfer coefficients.

From (23) following equations can be obtained:

Temperature of cold water in tank:

$$T_{cw} = \frac{1}{\beta^* - \beta} \left[\frac{g_1(t)}{c^*} \left(\frac{1 - e^{-c^* t}}{c^*} - \frac{1 - e^{-c^* t}}{c^*} \right) + \frac{g_2(t)}{c^*} \left(\frac{\beta^* (1 - e^{-c^* t})}{c^*} - \frac{\beta (1 - e^{-c^* t})}{c^*} \right) \right] + T_{hwo} (e^{-c^* t} - e^{-c^* t}) + T_{cwo} (\beta^* e^{-c^* t} - \beta e^{-c^* t}) \quad (24)$$

Temperature of hot water in tube :

$$T_{hw} = \frac{1}{\beta^* - \beta} \left[\frac{g_1(t)}{c^*} \left(\frac{\beta^* (1 - e^{-c^* t})}{c^*} - \frac{\beta (1 - e^{-c^* t})}{c^*} \right) + \beta^* \frac{g_2(t)}{c^*} \left(\frac{1 - e^{-c^* t}}{c^*} - \frac{1 - e^{-c^* t}}{c^*} \right) \right] + T_{hwo} (\beta^* e^{-c^* t} - \beta e^{-c^* t}) + \beta^* \beta T_{cwo} (e^{-c^* t} - e^{-c^* t}) \quad (25)$$

The instantaneous thermal efficiency (η) of MDSWH is given by

$$\eta_{th} = \frac{Q_{thermal}}{\sum(AI)} = \frac{mC_w (T_{cw} - T_{cwo})}{A_{tp} I_t(t) + A_s I_s(t) + (1 - \beta) A_{top} I_{top}(t) + A_E I_E(t) + A_W I_W(t)} \quad (26)$$

Electrical efficiency of a glass-to-glass PV module is given by (Aste et al., 2015)

$$\eta_e = \eta_o (1 - 0.0045 (T_{cell} - 25)) \quad (27)$$

Where, η_o is the efficiency of the cell under STC (standard test condition) i.e., $I = 1000 \text{ W/m}^2$ and $T_a = 25^\circ\text{C}$. Electrical output can be expressed as:

$$Q_{electrical} = \eta_e A_m I \quad (28)$$

The overall thermal efficiency and overall thermal energy gain of MDSWH can be expressed as (Singh et al., 2015)

$$\eta = \eta_{th} + \frac{\eta_e}{0.38} \quad (29)$$

$$\Sigma Q_{overall} = \Sigma Q_{thermal} + \frac{\Sigma Q_{electrical}}{0.38} \quad (30)$$

5. Results and Discussion

5.1 Simulated results of thermal model

PVNMSWH is simulated on MATLAB using various climatic, operational and design parameters and the simulated results have been validated with the experimental observations made on a particular clear sky day of April, 2017 and December, 2017 and plotted against time from 7:00hr to 17:00hr. The error (e) and correlation coefficient (r) between the experimental and simulated results have been calculated using Eqs.[29-31]

$$r = \frac{N \Sigma X_i Y_i - (\Sigma X_i)(\Sigma Y_i)}{\sqrt{N \Sigma X_i^2 - (\Sigma X_i)^2} \sqrt{N \Sigma Y_i^2 - (\Sigma Y_i)^2}} \quad (31)$$

$$e = \sqrt{\frac{\Sigma (e_i)^2}{N}} \quad (32)$$

$$e_i = \left[\frac{X_i - Y_i}{X_i} \right] 100 \quad (33)$$

N , X_i and Y_i are the numbers of observations, theoretical values and experimental values respectively.

Fig. 2 represents the variation of global solar radiation (I) and ambient temperature (T_a) with respect to time. The maximum intensity of measured solar radiation was found to be 1147 W/m^2 at 13:00 hr and 950 W/m^2 at 12:00hr on a particular day of April, 2017 and December, 2017 respectively.

Fig. 2. Hourly variation of climatic parameters.

Fig. 3 shows the hourly variation of cell temperature, coating temperature of PVNMSWH in the month of April and December, 2017. It can be observed from the figure that as the day proceeds, the increase in the cell temperature leads to decrement of electrical efficiency up to its maximum at 12:00 hr and then cell temperature retards again and thus results in the increase of electrical efficiency. Maximum cell temperature has been found to be 66.6°C and 39.6°C in the month of April and December respectively while cell efficiency is found to vary between 11-12%. The coating temperature increases with time and reaches its maximum at 17:00hr with 71.21°C and 50.8°C in April and December respectively. Coating temperature is the very important parameter as higher coating temperature leads to higher water temperature flowing in the tube just above the coating.

Fig. 3. Hourly variation of cell temperature, coating temperature, thermal and electrical efficiency

Fig. 4 shows the thermal efficiency and electrical efficiency of PVNMSWH for the month of April and December, 2017. The maximum thermal efficiency of 43.9% and 38.4% have been found to be of the PVNMSWH in April and December respectively at 13:00hr since maximum intensity of solar radiation is achieved during noon hours. The overall efficiency is the sum of thermal and equivalent electrical efficiency is found to vary between 30 to 69% and overall thermal energy produced by the system is obtained as 857kWh for the year 2017. The characteristic curve of PVNMSWH is shown in Fig. 5 with the maximum efficiency of 44%, negative slope depicting losses of PVNMSWH.

Fig. 4. Characteristic curve of PVNMSWH

Fig. 5. Hourly variation of hot water temperature for the month of April and December, 2017 in (a) storage tank and (b) tubes

Fig. 6. Hourly variation of hot water temperature for the month of April and December, 2017 in (a) storage tank and (b) tubes

5.2 Validation of model:

Fig. (6a) and (6b) shows the hourly variation of hot water temperature in the storage tank and the collector tubes respectively for a particular day of April, 2017 and Dec, 2017. The experimental and theoretical results have been found to be in well agreement. It can be observed that in the present system water temperature in tank is increasing till 17:00hr while in the conventional systems like FPC water temperature retards after 14:00hr (Hussain, 2003). This advantage is attributed to the advanced design of the PVNMSWH using transparent storage tank along with the use of thermally insulating materials. The transparent walls of the tank allow radiations to enter the tank during early morning and afternoon hours. Also, the circular tubes of the collector increase the solar exposure period which maintains the higher water temperature up to late evening hours. In FPC, glass and metals were used in the collector while in present system acrylic is used which is having lower conductivity (0.2 W/mk) and higher transmissivity (0.92) than conventional materials which leads to the lower heat loss and eliminates the need of further insulation. Thus, the system becomes lighter and cheaper. PVNMSWH properly utilizes the incident solar radiation because of the reduced gaps between tubes and no shading effect as the tubes are transparent. The maximum temperature of water in storage tank is obtained as 65.6°C and 49.0°C in the month of April and Dec, 2017 respectively at 17:00hr. Maximum variation of 4°C is obtained between theoretical and experimental values having the correlation coefficient of 0.99. It can also be inferred from the Fig. 3 and Fig 5 that the maximum variation of tank water temperature with ambient is found to be 27.6°C in April, 2017 and 30.1°C in December, 2017 at 17:00hr. The maximum theoretical water temperature of 64.7°C and 47.5°C in the month of April and December, 2017 respectively is obtained in the tank at 16:00hr. The maximum experimental water temperature of 60.4°C and 44.0°C is obtained in the tank at 16:00hr in the month of April and December, 2017 respectively.

5.3. Comparison of PVNMSWH and MDSWH with PV module

As mentioned in the section 1 (introduction), the FRP-thermocool assembly used as an insulation in the collector has been eliminated in the present design with an aim to provide hot water for the domestic use through a lighter and cheaper water heater than existing systems. In MDSWH of 100L, the water temperature attains the maximum value of 55°C at 17:00 hr for a particular day of April, 2017 and the present system of same capacity, as reported in section 5.2, attains the maximum value of 60.4°C in the same month. The variation in temperature can be attributed to the difference in the amount of solar radiation of different days and ambient temperature, wind speed etc., since both the observations have not been taken on same day. The maximum intensity of solar radiation was observed to be 853 W/m^2 when experiments were carried out for MDSWH and in case of PVNMSWH, the maximum intensity is 1146 W/m^2 . However, it can be concluded that almost same temperature of water is obtained in both the system while cost gets reduced by Rs. 5000 on eliminating the FRP-thermocool assembly. Thus, on removing insulation, the cost associated with the insulation gets reduced, making the system cheaper, without any compromise in the hot water temperature.

As mentioned in Tiwari and Dev (2019), the benefits of MDSWH over Flat Plate Collector, all benefits are associated with PVNMSWH also since both the systems are same except the insulation of collector. Thus, PVNMSWH is proved to be the best among the three collectors in terms of cost, weight and portability and hence can be recommended for domestic use.

6. Enviroeconomic and Cost Analysis

Enviroeconomic analysis is a very important tool to analyse the carbon mitigation. 0.982 kg of carbon dioxide is emitted into the environment for the production of 1 kWh electricity and annually CO_2 mitigation by PVNMSWH can be calculated as (Tripathi et al., 2016)

Table 3. Capital cost of PVNMSWH

Components	Quantity × Cost per item (Rs.)		Total cost of item (Rs.)	
	PVNMSWH	MDSWH	PVNMSWH	MDSWH
Inner Acrylic Tubes	10 × 125 per m	10 × 125 per m	1250	1250
Outer Acrylic Tubes	5 × 350 per m	5 × 350 per m	1750	1750
Fiber Reinforced Plastic	5.83 sq. ft × 320 per sq. ft	20.46 sq. ft × 320 per sq. ft	1865.6	6547.2
Acrylic Sheet	1.68 sq. m × 646 per sq. m	1.68 sq. m × 646 per sq. m	1084.8	1084.8
Iron Stand	12 kg × 75 per kg	12 kg × 75 per kg	900	900
Thermocole		0.64 sq. m		300
Solar PV Module	1	1	6000	6000
Taps	2 × 50 per piece	2 × 50 per piece	100	100
Black Paint	0.51	0.51	150	150
Fabrication Cost	(506+506*)× 4	(506+506*)× 4	4048	4048
Total cost			Rs.17,148.4 (231.61 US\$)	Rs.22,130 (344.56US\$)

$$\varphi_{CO_2} = \frac{\Psi_{CO_2} \times Q_{thermal}}{1000} = \frac{2.04 \times 857}{1000} = 1.748 \text{ tCO}_2e \quad (32)$$

Where, φ_{CO_2} is CO₂ equivalent intensity for generation of electricity and earned carbon credit (J_{CO_2}) is expressed as

$$J_{CO_2} = \varphi_{CO_2} \times j_{CO_2} = 1.784 \times 14.5 \times 74.04 \quad (33)$$

j_{CO_2} is termed as price of one tone of CO₂ which is 14.5 US \$ (as per KYOTO PROTOCOL) and the carbon mitigation cost of PVNMSWH is calculated as Rs.1915 per annum and the total capital cost of PVNMSWH is Rs. 17,148 as shown in Table3 which is the first time cost and hence will reduce for mass production. The capital cost is being recovered by its carbon mitigation cost only. The detailed enviroeconomic analysis of PVNMSWH is shown in tabular form in Table 4.

Table 4. Enviroeconomic analysis of PVNMSWH

Annual energy production cost		Rs. 4,184.15
CO₂ mitigation (tones/year)		1.784
Environmental cost (Carbon credit) for 15 years of lifespan	@14.5 US \$	Rs.28,725 (387.97 US \$)

7. Energy matrices

Energy matrices involves the effectiveness of the system in terms of energy required during its whole life cycle and energy produced. A new term is coined for the life cycle energy calculations called embodied energy. As per Treloar (1994) embodied energy is: "the quantity of energy required by all of the activities associated with a production process, including the relative proportions consumed in all activities upstream to the acquisition of natural resources and the share of energy used in all the equipments and in other supporting functions i.e. direct energy plus indirect energy". Using embodied energy, three basic matrices of energy is obtained (Agrawal and Tiwari, 2013)- the life cycle conversion efficiency (LCCE), the energy production factor (EPF) and energy payback time (EPBT).

$$(EPBT)_{En} = \frac{\text{Embodied energy}}{\text{Annual energy}(E_{out})} \quad (34)$$

$$(EPF)_{En} = \frac{\text{Annual energy}(E_{out})}{\text{Embodied energy}(E_{in})} \quad (35)$$

$$(LCC)_{En} = \frac{(E_{out} \times n) - E_{in}}{E_{solar} \times n} \quad (36)$$

Annual energy is the overall thermal energy gain and E_{solar} is the total annual solar energy incident on the water heater. The detailed embodied energy of each component is shown in Table 5 and the total embodied energy is calculated as 1088.04 kWh, which is 125 kWh lower than the embodied energy of MDSWH (Tewari and Dev, 2019) which indicates the present water heater requires lower energy. EPBT, EPF and LCCE is calculated as 1.5 years, 0.52 and 0.36 respectively for 15 years (n) of life the water heating system taking 275 days clear sky conditions of Allahabad.

8. Conclusions

The following conclusions have been drawn on the basis of present analysis.

- The modified design and thermally insulating material in collector tubes has reduced the need of external insulation, resulting light weight collector.
- PVNMSWH is providing same temperature of hot water as MDSWH with PV module at Rs. 5000 and 125kWh lower fabrication cost and embodied energy respectively.
- Overall efficiency of the PVT system has been found to vary between 30-69%.
- The maximum variation of tank water temperature with ambient is found to be 27.6°C in April, 2017 and 30.1°C in December, 2017 at 17:00hr.
- The carbon mitigation cost for PVNMSWH is calculated as Rs. 1915 per annum and the capital cost of the setup is Rs. 17,148.4 (231.61 US\$).
- The energy payback period, energy production factor and life cycle conversion efficiency is obtained as 1.9 years, 0.52 and 0.36 respectively.

Appendix A

A_b	Area of bottom wall of storage tank, m ² .
A_c	Area of coating, m ² .
A_E	Area of east wall of storage tank, m ² .
A_{iit}	Area of inner surface of inner tube, m ² .
A_{iot}	Area of outer surface of inner tube, m ² .
A_{oit}	Area of inner surface of outer tube, m ² .
A_{oot}	Area of outer surface of outer tube, m ² .
A_N	Area of north wall of storage tank, m ² .
A_s	Area of south wall of storage tank, m ² .
A_{top}	Area of top wall of storage tank, m ² .
A_w	Area of west wall of storage tank, m ² .
C_w	Specific heat of water, J/kg-K.
h_{bw}	Convective heat transfer coefficient between water in tank and inner surface of bottom, W/m ² K.
h_i	Radiative heat transfer coefficient between as between south, east, west and top surface of inner layer and inner surface of outer layer (W/m ² K).
h_o	Radiative –convective heat transfer coefficient between tube and ambient as well as between tank and ambient, W/m ² K.
h_{Tw}	Convective heat transfer coefficient between water in tank and south, east, west and top inner surface of inner layer, W/m ² K.

h_{nw}	Convective heat transfer coefficient between water in tank and inner surface of north, W/m ² K.
h_w	Convective heat transfer coefficient from water in tubes to inner surface of tube and coating, W/m ² K.
$I_c(t)$	Incident solar intensity on solar cell W/m ² .
$I_e(t)$	Incident solar intensity on east wall of tank, W/m ² .
$I_s(t)$	Incident solar intensity on south wall of tank, W/m ² .
$I_t(t)$	Incident solar intensity on collector, W/m ² .
$I_{top}(t)$	Incident solar intensity on top wall of tank, W/m ² .
$I_w(t)$	Incident solar intensity on west wall of tank, W/m ² .
K	Thermal conductivity of acrylic, W/m-K.
K_{ct}	Thermal conductivity of coating, W/m-K.
L	Length of tubes (m)
A	Mass flow rate of water, kg/sec.
M_{Tw}	Mass of water in tank, kg.
M_{nw}	Total mass of water in all tubes, kg.
N_t	No of tubes.
r_1	Inside radius of inner tube (m).
r_2	Outside radius of inner tube (m).
r_3	Inside radius of outer tube (m).
r_4	Outside radius of outer tube (m).
r_c	Inner radius of coating (m).
T_a	Ambient temperature, °C.
t_{acry}	Thickness of acrylic wall of tank, m.
T_{bi}	Inner surface temperature of bottom wall, °C.
T_{ct}	Temperature of coating, °C
T_{cw}	Cold water temperature in tank, °C.
T_{cwo}	Initial cold water temperature in tank, °C.
T_{Eii}	Inner surface temperature of inner layer of east wall, °C.
T_{Eio}	Outer surface temperature of inner layer of east wall, °C.
T_{Eoi}	Inner surface temperature of outer layer of east wall, °C.
T_{Eoo}	Outer surface temperature of outer layer of east wall, °C.
t_{FRPi}	Thickness of insulation, m.
t_{FRPt}	Thickness of wall, m.
T_{hw}	Hot water temperature in tank, °C.
T_{hwo}	Initial hot water temperature in tank, °C.
T_{ii}	Temperature of inner surface of inner tube, °C.
T_{io}	Temperature of outer surface of inner tube, °C.
T_{oi}	Temperature of inner surface of outer tube, °C.
T_{oo}	Temperature of outer surface of outer tube, °C.
T_{Ni}	Inner surface temperature of north wall, °C.
T_{sii}	Inner surface temperature of inner layer of south wall, °C.
T_{sio}	Inner surface temperature of inner layer of top wall, °C.
T_{wii}	Inner surface temperature of inner layer of west wall, °C.
U	Overall heat transfer coefficient from solar cell to ambient W/m ² K.
V_a	Velocity of air, m/s.

Greek Letters

α_c	Absorptivity of solar cell.
α_w	Absorptivity of water.
α_{acry}	Absorptivity of acrylic sheet.
α_{ct}	Absorptivity of coating.
$(\alpha\tau)_{eff}$	Product of absorptivity and transmittivity.
β_c	Packing factor.
τ_c	Transmittivity of solar cell.
τ_w	Transmittivity of water.
τ_{acry}	Transmittivity of acrylic sheet.
η_c	Thermal efficiency of solar cell.
ρ	Density of water (kg/m ³).

Appendix B

Various intermediate expressions used in thermal modelling:

All the evaluated parameters have been taken from Tewari and Dev [18] and can be referred from the same.

$$\frac{1}{U_{ld3}} = \frac{r_c \ln \left[\frac{r_1}{r_c} \right]}{k_c} + \frac{r_c \ln \left[\frac{r_2}{r_1} \right]}{2k_{acry}} + \frac{r_c}{(h_i + h_o)r_2} + \frac{r_c \ln \left[\frac{r_4}{r_3} \right]}{k_{acry}} + \frac{r_c}{h_o r_4}$$

$$\frac{1}{U_{2d3}} = \frac{A_w}{A_w h_w} + \frac{r_1 \ln \left[\frac{r_2}{r_1} \right]}{k_{acry}} + \frac{2r_1}{r_2 (h_i + h_o)} + \frac{2r_1 \ln \left[\frac{r_4}{r_3} \right]}{k_{acry}} + \frac{2r_1}{r_4 h_o}$$

$$a_1 = \frac{m_w C_w + A_w U_{2d3} N_t + h_w A_c - \frac{h_w^2 A_c}{h_w + U_{ld3}}}{M_{nw} C_w}$$

$$\frac{1}{U_{3d3}} = \frac{r_1 \ln \left[\frac{r_2}{r_1} \right]}{k_{acry}} + \frac{2r_1}{r_2 (h_i + h_o)} + \frac{2r_1 \ln \left[\frac{r_4}{r_3} \right]}{k_{acry}} + \frac{2r_1}{r_4 h_o}$$

$$\frac{1}{U_{4d3}} = \frac{2}{(h_i + h_o)} + \frac{2r_2 \ln \left(\frac{r_4}{r_3} \right)}{k_{acry}} + \frac{2r_2}{h_o r_4}$$

$$\frac{1}{U_{5d3}} = \frac{2r_3 \ln \left(\frac{r_4}{r_3} \right)}{k_{acry}} + \frac{2r_3}{r_4 h_o}$$

$$h_{o1} = \frac{k_{acry}}{r_2 \ln \left(\frac{r_2}{r_1} \right)}$$

$$h_{ct} = \frac{k_{ct}}{r_c \ln \left(\frac{r_1}{r_c} \right)}$$

$$b_1 = -\frac{m_w}{M_{Tw} C_w}$$

$$h_{o2} = \frac{k_{acry}}{r_4 \ln \left(\frac{r_4}{r_3} \right)}$$

$$h_o = 5.7 + 3.8v$$

$$T_{Eoo} = \frac{h_{kacry} T_{Eoi} + h_o T_a}{h_{kacry} + h_o}$$

$$h_{kacry} = \frac{K_{acry}}{t_{acry}}$$

$$T_{Eoi} = \frac{T_{Eio} (h_{ikacry} + h_{io}) + T_a h_{okacry}}{(h_{ikacry} + h_{io}) + T_a h_{okacry}}$$

$$T_{Eio} = \frac{T_{Eii} h_A + T_a h_B}{h_A + h_B}$$

$$T_{Eii} = \frac{\alpha_{acry} I_E(t) \tau_{acry} + h_{Tw} T_{cw} + h_c T_a}{U_1}$$

$$U_1 = \frac{h_{Tw} h_A + h_{Tw} h_B + h_B h_{kacry}}{h_A + h_B}$$

$$h_c = \left(\frac{h_{kacry} h_B}{h_A + h_B} \right)$$

$$T_{Wii} = \frac{\alpha_{acry} I_w(t) \tau_{acry} + h_{TW} T_{cw} + h_c T_a}{U_1}$$

$$T_{Sii} = \frac{\alpha_{acry} I_V(t) \tau_{acry} + h_{TW} T_{cw} + h_c T_a}{U_1}$$

$$T_{topii} = \frac{\alpha_{acry} I_H(t) \tau_{acry} + h_{TW} T_{cw} + h_c T_a}{U_1}$$

$$T_{No} = \frac{T_{Ni} h_{kFRP} + T_a h_o}{h_{kFRP} + h_o}$$

$$h_{kFRP} = \frac{K_{FRP}}{t_{FRP}}$$

$$T_{Ni} = \frac{\alpha_{FRP} I_V(t) \tau_{acry}^2 \tau_w + h_{NW} T_{cw} + T_a h_{kFRP-O}}{U_{2N}}$$

$$U_{2N} = \frac{h_{NW} h_o + h_{NW} h_{kFRP} + h_o h_{kFRP}}{h_o + h_{kFRP}}$$

$$h_{kFRP-O} = \frac{h_{kFRP} h_o}{h_o + h_{kFRP}}$$

$$T_{bi} = \frac{\alpha_{FRP} I_H(t) \tau_{acry}^2 \tau_w + h_{bw} T_{cw} + T_a h_{kFRP-O}}{U_{2b}}$$

$$U_{2b} = \frac{h_{bw} h_o + h_{bw} h_{kFRP} + h_o h_{kFRP}}{h_o + h_{kFRP}}$$

$$a_1 + \beta a_2 = c$$

$$b_1 + \beta b_2 = \beta c$$

$$\beta = \frac{-(a_1 - b_2) \pm \sqrt{(a_1 - b_2)^2 - 4a_2(-b_1)}}{2a_2}$$

$$a_2 = \left(-\frac{\dot{m}_w}{M_{Tw}} \right)$$

$$b_2 = \left(\frac{h_{tw} A_b + h_{NW} A_N}{M_{Tw} C_w} \right) + h_{TW}^2 \left(\frac{-A_S - A_E - A_W - A_{top}}{M_{Tw} C_w U_1} \right) + \frac{h_{TW}}{M_{Tw} C_w} (A_S + A_E + A_W + A_{top}) + \frac{1}{M_{Tw} C_w} \left(-\frac{h_{tw}^2 A_b}{U_{2b}} - \frac{h_{NW}^2 A_N}{U_{2N}} \right) + \frac{\dot{m}_w c_w}{M_{Tw} C_w}$$

$$g_2(t) = \frac{\alpha_w \tau_{acry}^2}{M_{Tw} C_w} (I_V(t) A_S + I_H(t) A_{top} + I_E(t) A_E + I_W(t) A_W) + \frac{\tau_{acry}^2 \alpha_{FRP} \tau_w}{M_{Tw} C_w} \left(\frac{I_H(t) h_{bw} A_b}{U_{2b}} + \frac{I_V(t) h_{NW} A_N}{U_{2N}} \right) + \frac{T_a h_{kFRP-O}}{M_{Tw} C_w} \left(\frac{h_{tw} A_b}{U_{2b}} + \frac{h_{NW} A_N}{U_{2N}} \right) + \frac{h_{TW} h_c T_a}{M_{Tw} C_w U_1} (A_S + A_E + A_W + A_{top}) + \frac{h_{TW} \tau_{acry} \alpha_{acry}}{M_{Tw} C_w U_1} (I_V(t) A_S + I_H(t) A_{top} + I_E(t) A_E + I_W(t) A_W)$$

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