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THEORETICAL ANALYSIS OF SOLAR WATER HEATING SYSTEM MADE OF NON-METALLIC MATERIALS

Rahul Dev

*Department of Mechanical Engineering, Motilal Nehru National Institute of Technology
Allahabad, Allahabad, Uttar Pradesh, India*
rahuldsurya@yahoo.com

Kirti Tewari

*Department of Mechanical Engineering, Motilal Nehru National Institute of Technology
Allahabad, Allahabad, Uttar Pradesh, India*

Dhananjay Singh

*Chemical Engineering Department, Institute of Engineering & Technology, Sitapur Road,
Lucknow, Uttar Pradesh, India*
dsa768008@gmail.com

Abstract

Solar Water heating is a renewable energy based technology. It requires solar radiation received from the sun to heat the water using thermosiphon process. In this paper, a solar water heater (SWH) of capacity 200 L is proposed which is made of non-metallic materials such as fibre reinforced plastic (FRP) and acrylic. A solar photovoltaic panel is also used to generate the electricity which can be used for the forced mode circulation of the water. A thermal model is developed and performance is analyzed for the climatic condition of Allahabad (25.4358° N, 81.8463° E). The result shows that the maximum water temperature in tubes of collector and

storage tank for the month of April are 66 °C and 64.2 °C respectively. Electrical efficiency and overall efficiency of the system has been found to vary between 10-11% and 20-23% for the month of April, 2016 respectively.

Keywords

Acrylic, Coating, Solar Water Heating, Thermal Model, Conventional Water

1. Introduction

Water heating contributes to a significant amount of energy consumption in the world, the growing concern of energy, surge in the depreciation of fossil fuels and the disastrous effects created by their use on global environment has added to the woes of the world fraternity, as such renewable energy sources envisage a promising factor to deal with these problems, Solar energy is one such source which can be utilized for water heating. These days' water heating and electricity production are being done simultaneously by integrating solar water heater with solar photovoltaic panels, which results in judicious and very promising step towards sustainable development (Charalambous et al., 2007).

Dubey & Tiwari, 2008 analysed an integrated combined system of photovoltaic glass – glass thermal solar water heater and applied energy balance equation for each component of integrated system. Efficiency of the combined system was found to be greater efficiency than flat plate collector and significant increase in efficiency from 33% to 64%.

Dev & Tiwari, 2012 analysed the performance of Evacuated tubular collector integrated solar still which is a source of distilled cum hot water, validated the results for the composite climate of Delhi by experiments performed from January to December 2008 and obtained annual thermal efficiency of 30.1%.

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 was based on basic energy balance for hybrid flat plate collector and storage tank, respectively. Extended the analysis for hot water withdrawal at constant collection temperature. Thermal efficiency of the system found to be increased with increase in constant flow rate and decrease in constant collection temperature. Efficiency was found to be maximum at hot water withdrawal flow rate of .006kg/s.

Along with development in integrated systems, modification in designs (Kim & Seo, 2007, Taheri et al., 2013, Krishnavel et al., 2014) and materials (Prakash et al., 1992) of existing systems have been done to improve the insulation and reduce the losses. Tewari &Dev, 2016 carried out performance analysis of Modified solar water heating system of 200L made of acrylic, FRP and metallic absorber plate, for summer and winter months of Allahabad which heated the water up to 73°C at 16:00hr in the summer month. Later Tewari &Dev, 2016 studied the performance of MSWHS with wind velocity, mass flow rate and absorptivity of absorber plate. Variation of wind velocity from 0.0m/s to 3.0m/s results in 2.12°C and 1.91°C variation in temperature of hot water in tubes and cold water in tank respectively which clearly states that convection losses get highly minimized and water temperature increases with decrease in mass flow rate of water and increase in higher absorptivity of metal plate.

Tewari &Dev, 2016 also modelled and studied the performance of Integrated Photovoltaic Solar Water Heating System with Absorber Coating on Inner Half of the Tube and found that maximum hot water temperature for the month of November is 53.6° and for the month of April the data is 71°C. Overall efficiency of the system found to vary between 27-31% for the month of April, 2015.

In present study, thermal modelling and theoretical analysis of SWH system made of non-metallic materials is carried out that has been integrated with PV to produce heat as well as electricity by capturing the solar radiations getting transmitted through PV module. Insulating material is used itself to capture the radiations which reduces the need of external insulation and hence cut the cost of insulation.

2. Experimental Setup

The following is the description of design, working principle of the proposed setup.

2.1 Design: The proposed design of SWH consists of a collector section and a storage tank with glass to glass PV module at its top. The collector is made of non-metallic materials –acrylic and FRP. The cylindrical collector tubes (made of acrylic with inner half coated with absorptive coating of SnS-CuxS) are connected with a trapezoidal water storage tank. North wall and base of storage tank of 200L is made of FRP and double layer of acrylic sheet is used in east, west, south and top wall of water tank. A glass to glass photovoltaic panel installed on the top of tank

of SWH to generate electricity. Orientation of this PV module is parallel to the tubes of collector so that perpendicular solar radiations fall on the PV module. In present design, use of metals have been eliminated which makes the system corrosion free. Cross-sectional view of collector tube and tank is shown in Figure1a and Figure1b respectively and solar water heating system is shown in Figure1c.

2.2 Working principle: The incoming radiation falls on the collector heat the water flowing in tubes and rest is transmitted to the coating. The coating gets heated which in turn again transmits its energy to the water in the tubes. Thus, water gets heated by combined effect of coating and directly falling solar radiations on tubes of the collector. Hot water with lower density moves upward and cold water having comparatively higher density will fill up its space tubes. Storage tank also contributes in heating of water during sunshine hours because of the transparent walls of acrylic. These walls are made in double layer which reduces heat loss during off sunshine and PV module attached with the system generates D.C power by gaining heat from the solar radiations falling on it which can be attached with DC pump to run the water in the system or it can be converted into AC to utilize it elsewhere.

In present paper, this power has not been utilized for running pump and hence the system is in passive mode.

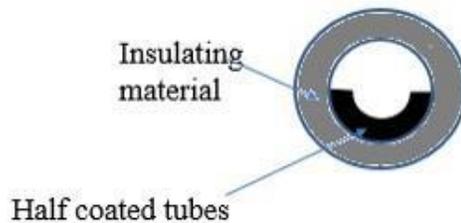


Figure 1a: Schematic diagram of acrylic tube with coating at lower half from inside.

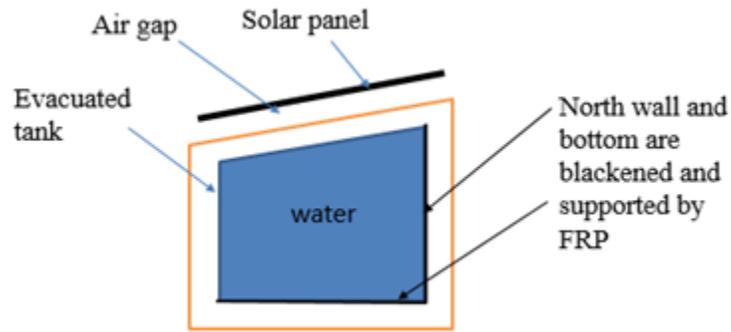


Figure 1b: Schematic diagram of water tank with a glass-glass solar panel.

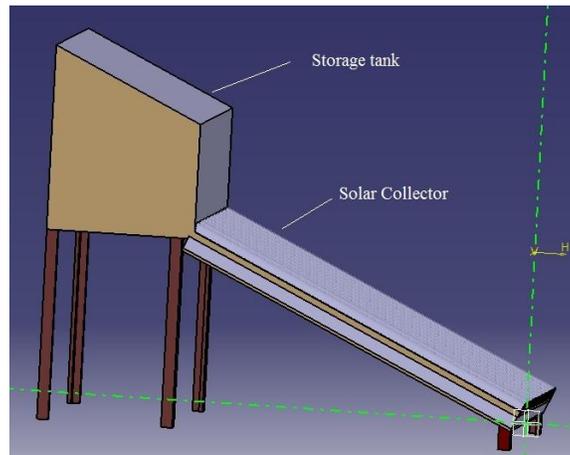


Figure 1c: Solar Water Heating System

3. Thermal Modeling

The following are the assumptions and the energy balance equations of each components of proposed SWH.

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

1. for solar cells of PV module:

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

2. for Coating:

$$\alpha_{ct} (\tau_{acry} \tau_w I_t(t)) A_c = h_w A_c (T_{ct} - T_{hw}) + U_{1d1} A_c (T_{ct} - T_a) \quad (2)$$

3. for water in tube:

$$\alpha_w [\tau_{acry} \tau_w I_t(t)] \frac{A_i}{2} + h_w A_c (T_{ct} - T_{hw}) = M_{hw} C_w \frac{dT_{hw}}{dt} + \dot{m}_w C_w (T_{hw} - T_{cw}) + U_{2d1} A_i (T_{hw} - T_a) \quad (3)$$

4. for inner surface of tube:

$$h_w \frac{A_i}{2} N_t (T_{hw} - T_i) + h_{ct} N_t A_c (T_c - T_i) = N_t A_i (T_i - T_a) U_{3d1} \quad (4)$$

5. for outer surface of tube:

$$h_{o1} (T_i - T_o) = h_o (T_o - T_a) \quad (5)$$

6. for water in storage tank:

$$\alpha_w \{I_V(t)A_s + I_H(t)A_{top}\} \tau_{acry}^2 + \alpha_w \{I_E(t)A_E + I_W(t)A_W\} \tau_{acry}^2 + h_{bw} A_b (T_{bi} - T_{cw}) + h_{tw} A_N (T_{Ni} - T_{cw}) + \dot{m}_w C_w (T_{hw} - T_{cw}) = M_{TW} C_w \frac{dT_{cw}}{dt} + h_{TW} A_s (T_{cw} - T_{sii}) + h_{TW} A_{top} (T_{cw} - T_{topi}) + h_{TW} A_E (T_{cw} - T_{Eii}) + h_{TW} A_W (T_{cw} - T_{Wii}) \quad (6)$$

7. for east wall (inner surface of inner layer):

$$\alpha_{acry} \{I_E(t)A_E\} \tau_{acry} + h_{TW} A_E (T_{cw} - T_{Eii}) = \frac{K_{acry} A_E (T_{Eii} - T_{Eio})}{t_{acryt}} \quad (7)$$

8. for east wall (outer surface of inner layer):

$$h_{kacry} A_E (T_{Eii} - T_{Eio}) = h_i A_E (T_{Eio} - T_{Eoi}) \quad (8)$$

9. for east wall (inner surface of outer layer):

$$h_i A_E (T_{Eio} - T_{Eoi}) = h_{kacry} A_E (T_{Eoi} - T_{Eoo}) \quad (9)$$

10. for east wall (outer surface of outer layer):

$$h_{kacry} A_E (T_{Eoi} - T_{Eoo}) = h_o A_E (T_{Eoo} - T_a) \quad (10)$$

11. for north wall (inner surface):

$$\alpha_{FRP} I_V(t) A_N \tau_{acry}^2 \tau_w = h_{Nw} A_N (T_{Ni} - T_{cw}) + \frac{K_{FRP} A_N (T_{Ni} - T_{No})}{t_{FRPT}} \quad (11)$$

12. for north wall (outer surface):

$$h_{kFRP}A_N(T_{Ni} - T_{No}) = h_oA_N(T_{No} - T_a) \quad (12)$$

From above equations, following equation for hot water temperature in tubes and storage tank can be obtained:

Temperature of water in tank:

$$T_{cw} = \frac{1}{\beta^+ - \beta^-} \left[\frac{1}{g_1(t)} \left\{ \frac{(1 - e^{-c^+t})}{c^+} - \frac{(1 - e^{-c^-t})}{c^-} \right\} + \frac{1}{g_2(t)} \left\{ \frac{\beta^+(1 - e^{-c^+t})}{c^+} - \frac{\beta^-(1 - e^{-c^-t})}{c^-} \right\} \right. \\ \left. + T_{hwo} (e^{-c^+t} - e^{-c^-t}) + T_{cwo} (\beta^+ e^{-c^+t} - \beta^- e^{-c^-t}) \right] \quad (13)$$

Temperature of hot water in tube:

$$T_{hw} = \frac{1}{\beta^+ - \beta^-} \left[\frac{1}{g_1(t)} \left\{ \frac{\beta^+(1 - e^{-c^-t})}{c^-} - \frac{\beta^-(1 - e^{-c^+t})}{c^+} \right\} + \beta^+ \beta^- \frac{1}{g_2(t)} \left\{ \frac{(1 - e^{-c^-t})}{c^-} - \frac{(1 - e^{-c^+t})}{c^+} \right\} \right. \\ \left. + T_{hwo} (\beta^+ e^{-c^-t} - \beta^- e^{-c^+t}) + \beta^+ \beta^- T_{cwo} (e^{-c^-t} - e^{-c^+t}) \right] \quad (14)$$

4. Methodology

A mathematical model i.e. thermal model of SWH is developed considering the energy balance equations of each component of the setup. The measured climatic data (solar radiation, ambient temperature, and wind speed) of Allahabad is used to check the performance of proposed SWH. The design parameters and operational parameters are also set for the same as shown in Table 1. Temperature of hot water in tubes and tank and efficiency of MSWHS is calculated in MATLAB model with the help of measured climatic data.

Table 1: Various design and operational parameters

Specifications	Values & Dimensions	Specifications	Values & Dimensions
α_{ct}	0.9	L	2 m
α_{FRP}	0.9	A_p	1.6 m ²
α_w	0.6	K_{acry}	0.2 W/m K
α_{acry}	0.05	r1	0.01m
τ_{acry}	0.92	rc	0.009m
τ_w	0.35	r2	0.0125m
h_i	2.55 W/m ² K	r3	0.022m
N_t	16	r4	0.025m
\dot{m}	0.02 kg/s	\dot{m}_w	0.02 kg/s
$V_{1\ tube}$	0.000314 m ³	M_{TW}	194.973 kg
V_T	200 L	K_{FRP}	0.0351 W/m K
M_{tw}	5.026 kg	h_p	200 W/m ² K
t_{FRPi}	0.0438 m	tFRPT	0.005 m
t_{acryt}	0.003 m	A_b	0.355 m ²
A_N	0.355 m ²	Space between tubes	0.0095 m
A_w	0.238 m ²	K_{ct}	0.5 W/m K
A_{top}	0.391 m ²	β	0.82

5. Results and Discussion

Temperature of water and coating are obtained for the month of April, 2016 with the help of the modelling and are plotted against time for portraying the working of the IPVTSWH in winters and summers. Figure 2 shows the hourly variation of hot water temperature in tubes of collector and storage tank with solar data for the month of April between 7:00hr to 17:00hr. From the result it is inferred that the water temperature in tank is lower than the water temperature in tubes, as the hot water existing from tubes get mixed with the comparatively colder water contained in storage tank. Maximum and minimum temperatures of tubes hot water in tubes have been found to be 66°C and 34°C at 16:00hr and 07:00hr respectively. Maximum and minimum temperatures of storage water have been found to be 64.62°C and 34°C at 17:00hr and 07:00hr respectively.

Figure 3 shows the variation of thermal efficiency of the SWH with time for a typical day of April month. Variation in thermal efficiency is directly proportional to the incident solar intensity, so it first increases and maximum efficiency of 23.5% is obtained at 12:00hr and then again decreases. Fig. 4 depicts the variation of electrical efficiency and overall efficiency of the system. These results show that the cell efficiency of the system decreases as the cell temperature increases and at the end of the day it again increases due to decrease in cell

temperature. On a typical day of April month, electrical efficiency has been found to vary between 10-11%.

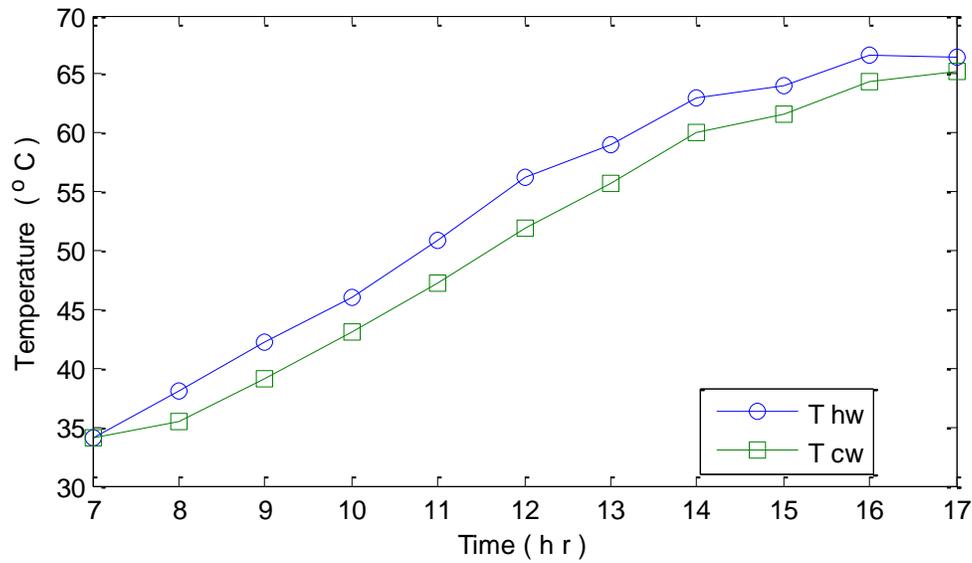


Figure 2: Variation of water temperatures in collector tubes and water tank

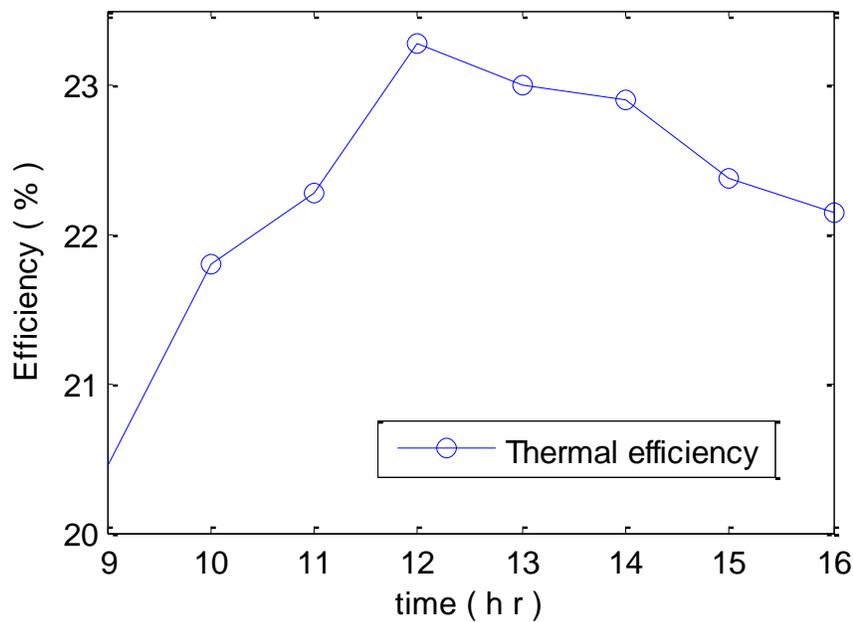


Figure 3: Hourly variation of thermal efficiency of SWH in the month of April

6. Conclusions

The following are the conclusions have been established based on present study.

- The design of collector and the tank section plays a pivotal role in enhancing the performance of the collector.
- Corrosion free system as metal has been eliminated, which is a major drawback of conventional solar water heaters.
- The selection of thermally insulating material (acylic) has reduced the need of external insulation, rendering the collector light weight (easy to transport) and reduced cost.
- The maximum variation of hot water and cold water temperature with ambient is found to be 25°C at 16:00hrs and 26°C at 17:00hrs respectively in April.
- Proposed design of SWH produces hot water as well as electrical power. Electrical efficiency is found to vary between 10-11% and overall efficiency of the system has been found to be 23%.

Exergy, energy analysis and improvement in efficiency of the system can be pursued for future work.

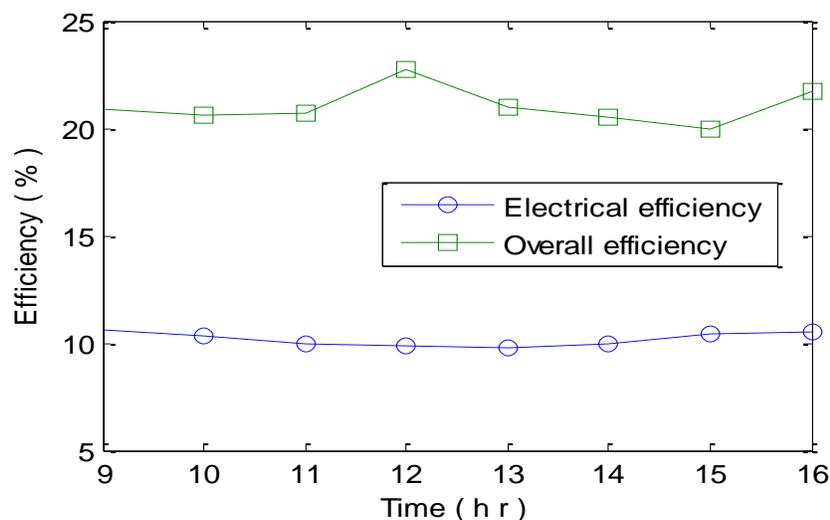


Figure 4: Hourly variation of electrical and overall efficiency in the month of April

6.1 Symbols

- T_{FRP} - Temperature of FRP sheet (°C)
- T_{oo} - Temperature of outer surface of outer tube of collector (°C)

- T_{oi} - Temperature of inner surface of outer tube ($^{\circ}\text{C}$)
- T_{io} - Temperature of outer surface of inner tube ($^{\circ}\text{C}$)
- T_{Eoo} - Temperature of outer surface of outer layer of east wall ($^{\circ}\text{C}$)
- T_{Eoi} - Temperature of inner surface of outer layer of east wall ($^{\circ}\text{C}$)
- T_{Eio} - Temperature of outer surface of inner layer of east wall ($^{\circ}\text{C}$)
- T_{No} - Outer surface temperature of north wall ($^{\circ}\text{C}$)
- T_{bi} - Inner surface temperature of bottom wall of tank ($^{\circ}\text{C}$)
- T_{Ni} - Inner surface temperature of north wall ($^{\circ}\text{C}$)
- T_{cw} - Temperature of water in tank ($^{\circ}\text{C}$)
- T_{hw} - Temperature of water in in tube ($^{\circ}\text{C}$)
- T_{hwo} - Initial water temperature in tubes of collector ($^{\circ}\text{C}$)
- T_{cwo} - Initial water temperature in storage tank ($^{\circ}\text{C}$)
- V_a - Velocity of air (m/s)
- T_a - Ambient temperature ($^{\circ}\text{C}$)
- N_t - No of tubes
- L - Length of tubes (m)
- A_{iit} - Inside area of inner tube (m^2)
- A_{iot} - Outside area of inner tube (m^2)
- A_{oit} - Inside area of outer tube (m^2)
- A_{oot} - Outside area of outer tube (m^2)
- R_{ii} - Inside radius of inner tube (m)
- R_{io} - Outside radius of inner tube (m)
- R_{oi} - Inside radius of outer tube (m)
- R_{oo} - Outside radius of outer tube (m)
- A_E - Area of east wall of storage tank (m^2)
- A_N - Area of north wall of storage tank (m^2)
- A_b - Area of bottom wall of storage tank (m^2)
- A_{FRP} - Area of insulation of FRP sheet (m^2)
- $I(t)$ - Solar radiation on collector (W/m^2)
- $I_s(t)$ - Solar radiation on south wall of tank (W/m^2)
- $I_E(t)$ - Solar radiation on east wall of tank (W/m^2)
- $I_w(t)$ - Solar radiation on west wall of tank (W/m^2)
- $I_{top}(t)$ - Solar radiation on top wall of tank (W/m^2)
- C_w - Specific heat of water ($\text{J}/\text{kg}\cdot\text{K}$)
- t_{FRPi} - Thickness of insulation (m)
- t_{FRPt} - Thickness of wall (m)
- t_{acry} - Thickness of acrylic wall of tank (m)
- K_{FRP} - Thermal conductivity of FRP ($\text{W}/\text{m}\cdot\text{K}$)

- Kacry- Thermal conductivity of acrylic (W/m-K)
- M_{tw} - Total mass of water in all tube (kg)
- M_{TW} – Remaining water mass in tank (kg)
- m – Mass flow rate of water (kg/sec)
- h_o - Radiative- convective heat transfer coefficient between outer acrylic tube and ambient as well as between walls of tank and ambient (W/m²K)
- h_i - Radiative heat transfer coefficient between outer surface of inner tube and inner surface of outer tube as well as between south, east, west and top outer surface of inner layer and inner surface of outer layer (W/m²K)
- h_p - Convective heat transfer coefficient between absorber plate and water in tube (W/m²K)
- h_{Tw} - Convective heat transfer coefficient between water in tank and south, east, west and top inner surface of inner layer (W/m²K)
- h_{nw} - Convective heat transfer coefficient between water in tank and inner surface of north wall (W/m²K)
- h_{bw} - Convective heat transfer coefficient between water in tank and inner surface of bottom surface (W/m²K)

6.2 Greek Letters

- ρ - Density of water (kg/m³)
- τ_w - Transmittivity of water
- τ_{acry} - Transmittivity of tubes.
- α_{FRP} - Absorptivity of FRP.
- α_w - Absorptivity of water.
- α_{acry} - Absorptivity of acrylic tubes.

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