Thermal and Economic Analysis of Low-Cost Water Heater made by Plastic Tub

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Abstract- The solar water heater is renewable technology that simply uses sunlight to heat water. Solar water heating Technology using sunlight is very useful for heating water for domestic as well as industrial use. This technology saves energy and reduces the load on non-renewable resources. Now a days electrical appliances are used to heat the water for domestic as well as industrial use, and this is a very expensive method of heating water. In areas where sunlight is available, the solar water heater can be used effectively for heating water with the help of Sunlight. This technology is less expensive compare to the electrical water heater as well as it is very useful for the areas where electrical power cut is a big problem. In this research paper a domestic plastic water storage container or tub is converted to a solar water heater and this design is further analyzed experimentally. The solar water heater design includes an insulated storage tub reflector made of card and an Aluminum foil floating cover made of bamboo strip. The suggested design of a solar water heater increases the intensity of solar energy for water heating applications and it is almost free for lower-income groups population, as the proposed water heater will cost only Rs 0.048/L (US$0.0006/L). A mathematical model has been developed for the proposed solar water heater and validated with the help of experimental results for a typical winter day in Raipur, CG, India (21.2514°N, 81.6296°E). The proposed water heater is compared with and without the reflector. It has been observed that the heater with a reflector shows better performance than a heater without a reflector. The maximum water temperature achieved in a day is 37.6 °C, water is heated maximum up to 17.6°C for heater with reflector. The total amount of heat energy supplied for a day is 1812.2kJ which is about 13% more than the total heat supplied to water without heater. This technology is very useful and cheaper in cost as compare to electrical water heating or any other type of water heating sources. The daily thermal efficiency of proposed heater is 27.2%.

Keywords –Economical Water Heater, Floating Cover, Reflector, Degree of Heating, Heat Supplied.

1. Introduction

Due to the scarcity and expense of traditional energy sources, low-income individuals in India typically utilize wood or charcoal to heat water during the winter months. However, researchers from all around the world are constantly working to improve efficiency of solar energy and impact of Renewable energy [1] even more. Various researchers are working to develop and encourage solar Energy market [2] There is always a need to come with a cheap water heating solution for rural population. One such solution for meeting the demand for hot water in rural areas is to make use of solar water heaters. The cost of centralized water heaters put on the roof is high, and they are only available in urban regions. Electric geysers and immersion rods both use pricey electrical energy to heat water. Certain low-priced solar water heaters have been developed in recent years to meet rural areas demand of water. As of now Batch water heaters (Collection/Storage water heaters) are a simple and low-cost way to heat water. Water heaters of the collection/storage type have been the subject of research by a number of academics [3-8]. Besides these, other proposals for inexpensive water heaters can be discovered in work by [9-13]. Few other methods of improvement of performance of heaters are discussed by [14-20]

Few studies have looked into the economic aspects of the heater. [21] Recently developed a low-cost flat plate water heater and tested their prototype for efficiency; they replaced the copper collector with aluminium, lowering the overall cost to Rs - 11,120/- for 100 LPD. [22] created a spread sheet-based financial model to calculate the output variables of a solar water heater, such as the discontinued payback period, net present value, and so on. [23] evaluated the scientific and fiscal feasibility of domestic solar water heaters and discovered that single evacuated tube solar water heaters produce the highest solar fraction of 69%. [24] investigated the thermal effectiveness and cost investigation of a Rawanda-made solar water heater; they replaced the collector's galvanized iron sheet with an aluminium sheet to reduce costs.

Recently,[25] proposed a cheap water heating solution for people belonging to lower income groups. They suggested to use a single glazed floating cover to be placed over the bucket/tub containing water. The ring-shaped cover is constructed from bamboo strips found locally; the top face is glazed with transparent polythene, while a black polythene sheet is used to is covered bottom face as shown in Fig.1.

Fig.1. Floating Cover made by Bamboo

They recommended the cover to be placed over bucket/tub containing water, after passing through the top glazed face; the solar radiation is absorbed by the black polyethene sheet. As a result, the water in contact receives and is heated. The hot water can be used for a variety of household tasks later in the day.

In the current research, authors advised attaching a reflector made of inexpensive card stock with aluminum foil taped over it to improve the performance of the prior design. The floating cover will receive more solar radiation due to reflector. The heater's performance will improve as a result of receiving direct and reflected radiation. The proposed water heater's mathematical model has been prepared and experimentally verified at Raipur, CG, IND (21.2514° N, 81.6296° E). The effectiveness of the new heater with reflector and the previously proposed heater design without reflector was compared. To ascertain the price of heating water, authors also carried out a simple fiscal analysis to conclude the expenditure of heating the water.

The water temperature inside the heater will depend on how much heat comes from the sun and how much heat is lost from the system as a whole. In this work, the authors ran tests to figure out the overall heat loss coefficient. The proposed heater is placed outside in the shade (to overcome any radiation through sun) and filled with hot water. The rate at which the water cools has been measured to figure out the overall heat loss coefficient (top, sides and bottom loss).In this work authors determine the daily thermal efficiency of proposed heater.

2. Mathematical Analysis

2.1. Loss Coefficient Computation[25]

The energy equilibrium of hot water in the tub is specified by,

$$M_w c_w \frac{dT_w}{dt} = -(Q_T + Q_s + Q_b) \tag{1}$$

In above Eq. M_w is Total mass of water in heater, c_w is Specific heat of water, Q_T, Q_s & Q_b is heat transfer rate from the top, side and bottom surface $\dot{Q}_T$, $\dot{Q}_s$ and $\dot{Q}_b$ are given by

$$\dot{Q}_T = (h_c + h_r) A_t (T_w - T_a) \tag{2}$$

In Eq. 2 h_r & h_c are radiative and convective heat transfer coefficient from top

$$\dot{Q}_s = h_s A_s (T_w - T_a) \tag{3}$$

$$\dot{Q}_b = h_b A_b (T_w - T_a) \tag{4}$$

Eq. 1 can be written as,

$$M_w c_w \frac{dT_w}{dt} = -U_L (T_w - T_a) \tag{5}$$

Overall heat transfer coefficient U_L , between water & air is specified by,

$$U_L = (h_c + h_r) A_t + h_s A_s + h_b A_b \tag{6}$$

A_t , A_s , A_b area of heater at top, side & bottom

Eq.4 gives,

$$U_L = -\frac{M_w c_w}{t} \ln \frac{(T_w - T_a)}{(T_{w0} - T_a)} \tag{7}$$

2.2. Calculation of Transient Water Temperature

The energy balance of water kept in a tub in the sun is determined by,

$$M_w c_w \frac{dT_w}{dt} = (\alpha\tau)[S(t) A_t + \rho S'(t) A_r] - U_L (T_w - T_a) \tag{8}$$

Eq. 8 can be written as

$$\frac{dT_w}{dt} + K_1 = K_2(t) \tag{9}$$

Some assumptions have been made to solve Eq. 9[26]

(i) The time interval $dt(0 < t < dt)$

(ii) The function $K_2(t)$ is considered constant, i.e, $K_2(t) = \overline{K_2(t)}$ for small time interval dt

(iii) K_1 is a constant during the time interval

The temperature of the transient water will be furnished by,

$$T_w = \frac{\overline{K_2(t)}}{K_1}[(1 - \exp(-K_1 t)] + T_{w0}\exp(-K_1 t) \tag{10}$$

Constants are,

$$K_1 = \frac{U_L}{M_w c_w}$$

and

$$K_2 = \frac{(\alpha\tau)[S(t)A_t + S'(t)A_r] + U_L T_a}{M_w c_w}$$

The time required for water to reach a specific temperature

(Tw) is deduced from Eq. 9. $t = \frac{-1}{K_1}\ln[\frac{(T_w - \frac{K_2}{K_1})}{(T_{w0} - \frac{K_2}{K_1})}]$ (11)

3. Experimental Analysis

3.1. Determine Overall Heat Loss Coefficient

To measure the overall coefficient of heat loss, the experiment was conducted outdoors in the shade. By Filling the bathtub with hot water and measuring the rate of cooling after every 8 minutes between 9 a.m

Table 1. Range make and Accuracy of Gadget used during Experiment

Gadget	Scope	Precision	Uncertainty
Temperature Sensor K type-constantan	0ºC to 150ºC	±0.2ºC	2.0% to 0.4% (10ºC - 50ºC)
RTD-Platinum Temperature Sensor	-50ºC to 199.9ºC	±0.1ºC	1% to 0.2% (10ºC to 50ºC)
Digital Anemometer	0.00m/sec to 45.00m/sec	±0.1m/sec	5.0% (2m/sec)
Kipps & Zenon Pyranometer	0W/m^2 to 1500W/m^2	73.0µV/W/m^2 (Sensitivity)	10.0%
Stop Watch	-	±0.01s	-

Average water temperatures at depth of 5cm, 10cm, and 15cm have been reported. An RTD setup outside measures the ambient air temperature. The entire heat loss coefficient was calculated using Equation 7 and Table 1 provides information on the numerous instruments utilised during the experiment.

The loss coefficient value is obtained and displayed in Table 2. Loss coefficient values range between 2.5 W/ºC and 4.3W/ºC. The slight fluctuation is a result of the fluctuating wind speed during the experiment. For further calculations, the average loss coefficient value is assumed to be 3.2 W/ºC

Table 2. Overall Heat Transfer Coefficient (U_L) during Experiment

t	T_a	T_w	U_L
9.00 AM	23.8	45.8	2.9
9.08 AM	23.8	45.5	3.0
9.16 AM	23.7	45.2	3.0
9.24 AM	23.8	44.9	3.1
9.32 AM	23.8	44.7	2.1
9.40 AM	23.9	44.4	3.2
9.48 AM	23.9	44.1	3.2
9.56 AM	24.0	43.7	4.3
10.04 AM	24.6	43.5	2.3
10.12 AM	25.7	43.3	2.5
10.20 AM	26.8	43.0	4.0
10.28 AM	25.4	42.8	2.5
10.36 AM	24.9	42.6	2.5
10.44 AM	25.3	42.4	2.6
10.52 AM	25.3	42.1	3.9
11.00 AM	25.3	41.8	3.9
11.08 AM	25.2	41.6	2.7
11.16 AM	25.2	41.3	4.0
11.24 AM	25.1	41.1	2.8
11.32 AM	25.1	40.9	2.7
11.40 AM	25.2	40.7	2.8
11.48 AM	25.2	40.5	2.8
11.56 AM	25.3	40.2	4.3

3.2. Effectiveness of the Suggested Heater

We conducted an experiment in the climate of Raipur, CG, India on a typical winter day (Jan. 25, 2022) to evaluate the effectiveness of the suggested heater with attached reflector. The effectiveness of the heater with reflector has been compared with the performance of the previous proposed design of heater without reflector. In addition, the mathematical model was validated by comparing experimental results with theoretical readings.

Table 3. Dimension of Proposed Heater

S. No	Parameters	Dimensions
1	Diameter of Tub	0.43 m
2	Depth of Tub	0.21 m
3	Capacity of Tub	25 L
4	Diameter of Floating Cover	0.42 m
5	Thickness of Floating Cover	3.1 cm
6	Height of Reflector	0.30m
7	Breadth of Reflector	0.41 m
8	Insulation Thickness (Thermocol)	2.5 cm

The suggested heaters of same capacity one with reflector and another without reflector were placed outside in the sunlight and pour with water at 8:00 am in the morning. The floating cover was positioned over them such that the lower black face touched the water and the upper glazed face faced the sun. Solar energy passedthrough the upper face and was then absorbed by the bottom black face.Due to the lower face's absorption of sun light, the water in contact with it becomes heated.The water temperature was measured at 30-minute intervals. The actual photograph of experiment is revealed in Fig.2 and the dimensions of the proposed heater is illustrated in Table 3

The theoretical temperature of water was computed by Eq.9. Ambient air temperature and solar radiation incident on heater during experiment were recorded and shown in Figs 3 &4

Fig. 2 Actual Photograph of Experiment

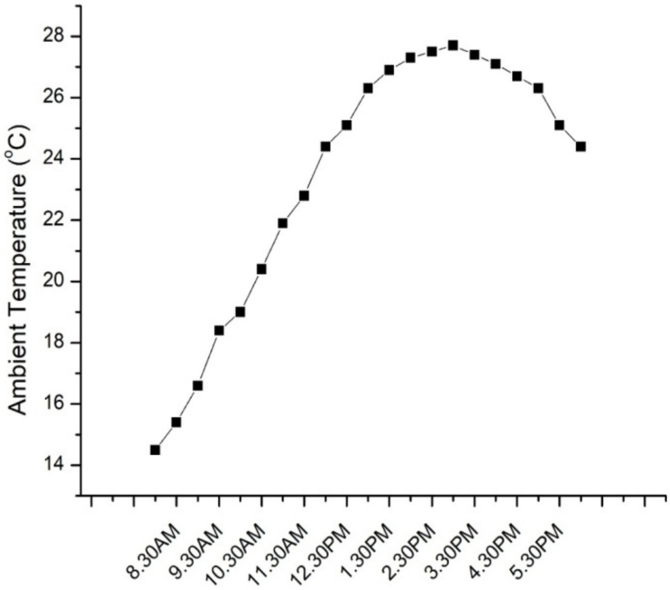

Fig.3 Recorded Ambient Temperature during Experiment

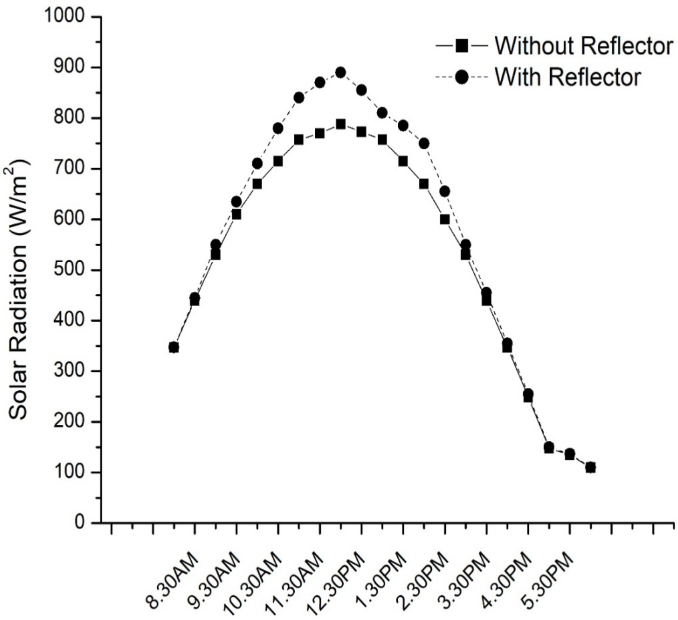

Fig.4 Recorded Solar Radiation on both Heaters during Experiment

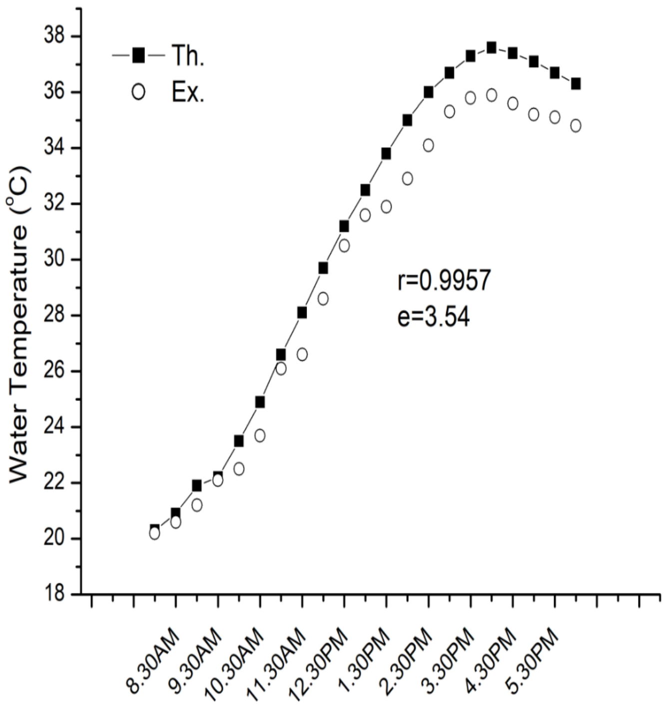

Fig.5. Experimental and Theoretical Water Temperature for Heater with reflector

The theoretical & experimental water temperatures are fairly close. The correlation coefficient (r) and percentage deviation of root mean(e) indicate how close the experimental and theoretical values. The correlation coefficient and root mean standard deviation are provided by,

$$r = \frac{N\sum X_{pre}X_{\exp} - (\sum X_{pre})(\sum X_{\exp})}{\sqrt{N\sum X_{\exp}^{2} - (\sum X_{\exp})^{2}}\sqrt{N\sum X_{pre}^{2} - (\sum X_{pre})^{2}}} \quad (12)$$

$$e_i = [\frac{X_{pre(i)} - X_{\exp t(i)}}{X_{pre(i)}}]\times 100 \quad (13)$$

Fig. 5 also shows the correlation coefficient and the percentage deviation of root mean. When the degree of freedom is set to 21, the correlation coefficient (r) is approximately 0.9995.It appears to be suitable for solar thermal experiments. Furthermore, percentage deviation of root mean is 3.5

4. Determination of Thermal Efficiency

The daily thermal efficiency of the water heater will be given by,

$$\eta_{th} = \frac{M_w c_w (T_{wo} - T_{wi})}{Adt\sum I} \quad (14)$$

In Eq. 14, M_w is the mass of water in heater (tub), c_w is the specific heat capacity of water, T_{wo} is the temperature of water outlet from heater (when the temperature of water is maximum) T_{wi} is the temperature of inlet water (at the time of filling water in morning). A is the surface area of heater and ΣI is the total amount of solar radiation received till the maximum temperature is reached.

The thermal efficiency of the proposed heater has been computed. The hot water is supposed to be extracted from heater around 12:30PM when it reaches to maximum. The difference in temperature of water is 17.6oC and the total amount of solar radiation received till 12:30PM is 3255W/m2. The thermal efficiency computed by Eq. 14 is 27.2%.

5. Results and Discussions

The current study offers a feasible method for raising the effectiveness of open water heating in the sun. The straightforward storage container can be converted to a water heater which gathers and stock water. The sides and bottom of the water-carrying plastic tub are insulated with thermocol sheets, while the top is protected by a single glazed floating cover. A simple card made reflector cover is attached to enhance the amount of solar radiation received by floating cover. The total solar energy incident on cover will be absorbed by the water in the tub. The proposed heater's mathematical model was created andexperimentally verified for the climate in Raipur, CG, India.By measuring the rate at which water cools, an experiment has been done to establish the overall loss coefficient.

The performance of the proposed heater with reflector has been compared with the performance of heater without reflector. The transient temperature of water is computed at time interval of 30 mins for both heaters and shown in Fig. 6.

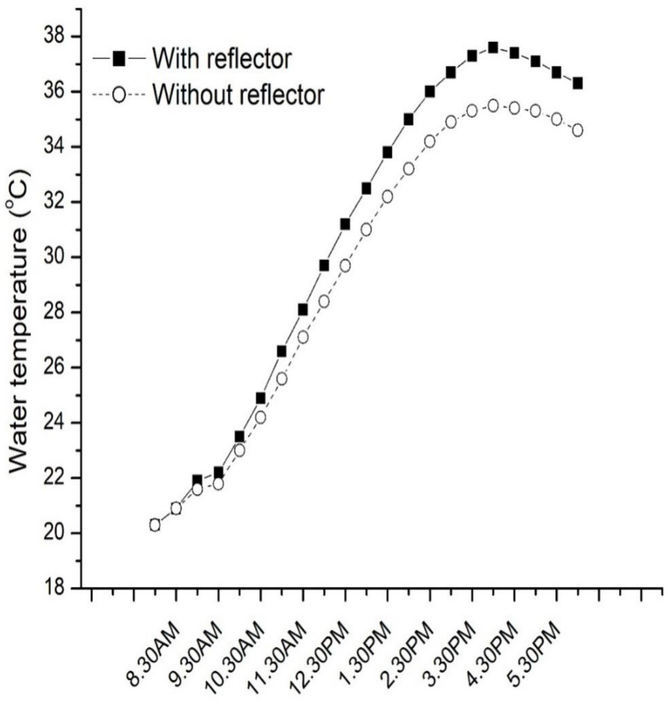

Fig.6. Water Temperature of Heater with and without Reflector

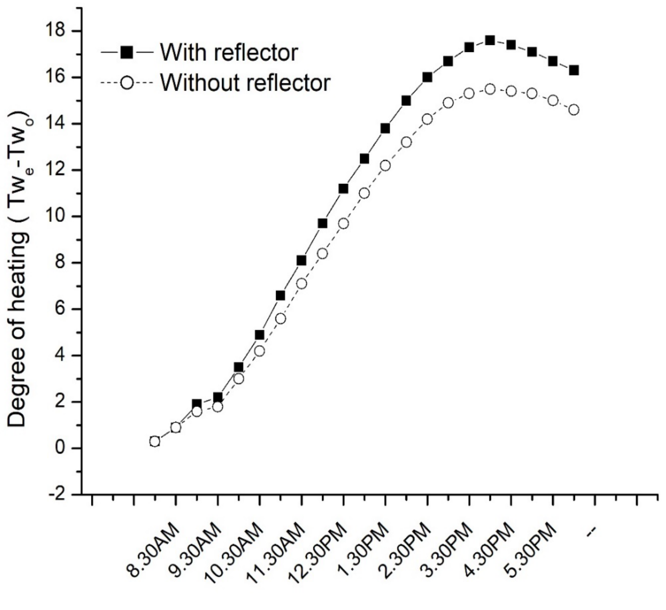

Fig.7. Degree of heating of

It is seen that the maximum water temperature reached for heater with reflector is 37.6ºC where as the maximum temperature reached for heater without reflector is 35.5ºC. The maximum water temperature reached for heater with reflector is 1.5ºC more than heater without reflector. The degree of heating of water is computed for both heaters as shown in Fig.7. The value comes out as 17.6ºC for heater with reflector whereas 15.5ºC without reflector

The total heat energy transferred to water for 30 mins for a day is given by

$$E = M_w c_w (T_{we} - T_{wi}) \quad (13)$$

$$TE = \sum_{day} M_w c_w (T_{we} - T_{wi}) \quad (14)$$

The total heat energy transmitted to water (Useful heat) for a winter day in Raipur, Chhattisgarh has been calculated. It is seen from Fig.8, thatthe total heat energy supplied to water is 1812.2kJ for heater with reflector and for the heater without reflector the total heat energy transferred is 1602.7kJ.

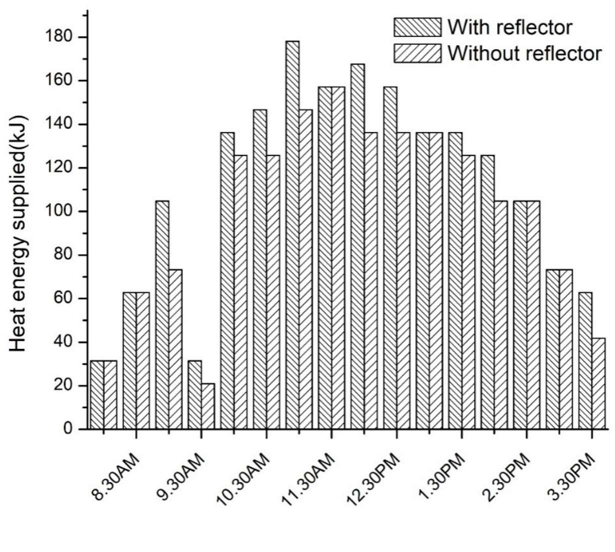

Fig.8. Heat Energy Supplied (kJ)

6. 6. Engineering Economic Analysis

The cost of fabricating a water heater with a reflector cover is shown above in Table 4.

Table 4. Cost of Fabricating a Water Heater with a Reflector

S.No	Particulars of Item	Cost (In Rs)
i.	Strip price	20/-
ii.	Price of a transparent plastic sheet	10/- (@Rs100/kg)
iii.	Price of a black polythene sheet	12/-(@Rs120/kg)
iv.	Price of thermocolinsulation	20/- (@ Rs 10 per sheet)
v.	Glue price	5/-
vi.	Rubber price	5/-
vii.	Tape price	12/-
viii.	Cost of card board	15/-
ix.	Cost of aluminium foil	11/-
x.	Total capital cost	110/-

The price of the water storage tub is excluded. The tub is commonly found in homes for a variety of domestic purposes. While performing economic analysis we have considered the rate of interest on capital cost to be around 10%, the total life of the heater is taken as 3 years. Annual maintenance cost considered is negligible

The total annual cost (TAC) will be given by

TAC=(CC)x (CRF)+(AMC) -(SV) x (SFF) (15)

In above equation CC is the total capital cost, CRF is the capital recovery factor, AMC is the annual maintenance cost, SV is the salvage value and SFF is the sinking fund factor. In Eq. 15, AMC and SV has been neglected (cost of scrap is neglected). CRF is given by,

$$CRF = \frac{i(1+i)^n}{(1+i)^n - 1} \quad (16)$$

The TAC as determined by Eq. 15, considering total life n as 3 years and at 10% rate of interest, will be equal to TAC=Rs37.73

The cost included in above table is as per market cost in Raipur, Chhattisgarh, India. The daily hot water produced by proposed heater is 25L/day. The total annual hot water produced will be given by

$$(THW)_a = \sum (THW)_d N \quad (17)$$

Here $(THW)_d$ is the total hot water produced in a day and N is the number of days for winters in a year. For winter months (Dec., Jan and Feb.) the number of days is 91. The total hot water produced annually is 2275L.

The cost of hot water produced per litre will be given by,

(Cost/L= TAC/Total hot water produced annually)

which is equal to Rs0.0165/L(US$0.00002/L).

7. Conclusions

The suggested course of action is doable and affordable for individuals with lower earnings.For a range of household chores, you can use the hot water that is accessible in the middle of the day and in the evening. During a winter day in Raipur, Chhattisgarh, water can heat to a high of 17.6oC. The water temperature in the late afternoon and evening ranges from 35 to 40 degrees Celsius. The proposed water heater with reflector is cost-effective and accessible to those from lower socioeconomic groups. The expenditure of water produced is Rs0.0165/L(US$0.00002/L).

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Nomenclature

h_c	Heat transfer coefficient (convection) from top	$Wm^{-2}K^{-1}$
h_r	Heat transfer coefficient (radiation)from the top	$Wm^{-2}K^{-1}$
h_b	Overall heat transfer coefficient between bottom to ambient	$Wm^{-2}K^{-1}$
h_s	Overall heat transfer coefficient between sides and ambient	$Wm^{-2}K^{-1}$
$\dot{Q}_T$	Heat transfer rate from the top surface	W
$\dot{Q}_s$	Heat transfer from sides	W
$\dot{Q}_b$	Heat transfer rate from bottom	W
M_w	Total mass of water	kg
S	Solar radiation intensity(Direct)	Wm^{-2}
S'	Solar radiation ntensity(Reflected)	Wm^{-2}
T_a	Ambient temperature	^oC
T_w	Water temperature	^oC
U_L	Overall heat transfer coefficient	Wm^2K^{-1}
$\alpha\tau$	Effective transmittance-absorptance product	
c_w	Specific heat of water	J/kgK
A_t	Area of floating cover	m^2
A_r	Area of reflector	m^2
M_w	Mass of water in heater	kg
c_w	Specific heat of water	J/kgK
T_{w0}	Initial water temperature at time t=0	^oC
t	Time	s
A_s	Area of heater at side	m^2
A_b	Area of heater at bottom	m^2
ρ	Reflectivity of cover	

Constants: -

$$K_1 = \frac{U_L}{M_w c_w}$$

$$K_2 = \frac{(\alpha\tau)[S(t)A_t + S'(t)A_r] + U_L T_a}{M_w c_w}$$