Experimental evaluation of solar integrated water heater

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Abstract:

Domestic immersion heaters used for heating of cold water has an electrical resistance heating element encased in a tube and directly placed in it. Most common method for heating of cold water is use of portable immersion rod water heater in open bucket operated in operators control without controller unit (thermostat).

This paper presents an experimental evaluation of portable modified conventional buckets of 10 l capacity. Out of ten modified portable storage, best three cases (viz. Non-insulated open plastic bucket (OPB), Non insulated plastic bucket top surface covered with a transparent cover (CPB), and Insulated plastic bucket closed with a transparent cover (ICPB)) are discussed. Maximum temperature rise after two hour time duration OPB, CPB, and ICPB are 29.82%, 47.36%, and 21.49% respectively as compared with the initial value the temperatures (22.8 °C). At 14:45 hour CPB temperature reaches 35.6 °C which is 17.88 and 23.61% higher values as compared to the OPB and ICPB units. Net saving due to utilization solar energy in CPB for a range of 35-50°C is net saving increased by 12.34%, 25.76%, 40.73%, 57.93%, 76.45%, and 97.18% from 2017 to 2022 as compared with the saving in 2016.

Keywords: Solar water heater; Heat and mass transfer; Modified conventional bucket, power saving; cost analysis.

Symbols

- $A_B$ Bottom surface area of bucket, $m^2$
- $A_T$ Top surface area of water, $m^2$
- $A_S$ Area of sides, $m^2$
- $C_B$ Initial investments in bucket, insulation, and cover, INR
- $C_E$ Electricity rate, INR/kW
- $C_H$ Initial investment cost of an immersion rod, INR
- $C_T$ Total system annual cost, INR
- $C_u$ Overall cost of the useful energy, INR/kWh

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\( C_w \)  Specific heat of water, \( J/kg^\circ C \)  
\( C_{TA} \)  Total annual cost of the system, \( INR \)  
\( E_e \)  Electrical energy supplied through emersion rod, \( W \)  
\( E_s \)  Solar energy received, \( W \)  
\( E_T \)  Total energy supplied to the bucket through the solar and electrical source, \( W \)  
\( h_B \)  Total heat transfer coefficient from the water to the ground through the bottom, \( W/m^2 \^\circ C \)  
\( h_c \)  Convective heat transfer coefficient from top surface /water to ambient air , \( W/m^2 \^\circ C \)  
\( h_r \)  Radiative heat transfer coefficient from cover surface /water to ambient air, \( W/m^2 \^\circ C \)  
\( h_s \)  Total heat transfer coefficient from water to the ambient air through sides, \( W/m^2 \^\circ C \)  
\( M_w \)  Mass of water, \( kg \)  
\( P_a \)  Partial pressure of saturated water vapour at ambient temperature, \( N/m^2 \)  
\( P_w \)  Partial pressure of saturated water vapour at water temperature, \( N/m^2 \)  
\( T_w \)  Temperature of water, \( ^\circ C \)  
\( T_a \)  Ambient temperature, \( ^\circ C \)  
\( Q_c \)  Convective heat loss from water/ top surface to surrounding, \( W \)  
\( Q_e \)  Evaporative heat loss from water/ top surface to surrounding, \( W \)  
\( Q_r \)  Radiative heat loss from water/ top surface to surrounding, \( W \)  
\( Q_{net \ loss} \)  Heat loss through lateral surface of bucket, \( W \)  
\( Q_u \)  Annual useful energy, \( kWh \)  
\( Z \)  Percentage rate of interest  
\( \varepsilon_{eff} \)  Effective emissivity of cover/ water surface  
\( v \)  Velocity of air, \( m/s \)  
\( \sigma \)  Stefan-Boltzmann coefficient, \( ( = 5.67 \times 10^{-8} W/m^2 K^4 ) \)  
\( \gamma \)  Relative humidity
1. **Introduction**

The demand for domestic electrical power consumption is increasing day by day due to the population escalation in rural and urban areas of the developing nations. A significant portion of domestic power is consumed for heating of cold water in winter bathing. A detailed review of the study of several solar water heaters has been reported by Raisul Islam et al. [1]. Several portable and fixed types of solar water heaters are currently available in the market, with the long range of an initial investment cost but still, their prices are too high as compared with the emersion rods. Role of nano-fluid in solar water heating system investigated and reported by Natarajan and Sathish [2]. Parametric study of domestic solar water heaters has been reported by many researchers [3,4]. Utilization of an electrical emersion rod in the bucket for heating of the cold water in winter session is a most common practice especially within the rural and urban area due to the low initial investment cost of the electric emersion rod. The techno-economic water heating system in a bucket with the help of emersion rod has been evaluated by Sodha et al.[5]. They have suggested three different methods for its improvement, viz. (i) Insulating lateral and bottom surface, (ii) Augmented with the floating cover over water surface, and (iii) Augmented with both. Experimental evaluation of the heat flux and heat transfer coefficient using inverse method has been reported by Farahani et al. [6]. Design and simulation of water heating system has been reported by Zhang et al. [7]. A case study of the new design of an evacuated tubular water heater performance in the climatic condition of Michigan’s has been reported by Mamouri and Bénard [8]. Life cycle assessment of domestic water hot water cycle has been reported by Moore [9]. Evacuated tube collector water heater with the multilayer absorber has been reported by Sobhansarbandi et al. [10]. Average economic performance of solar water heater has been reported by Ferrer [11].

As in most of the rural areas of the different countries still peoples are using electric emersion rod for water heating if they can motive to have partial or full utilization of solar energy using the proposed methodology, It may reduce domestic power consumption to large extent.

2. **Experimental Setup**

Actual photograph and schematic view of the portable water heater augmented with the incident solar radiations are shown in Fig. 1a and 1b respectively. As the black color surface has a better coefficient of absorption as compared with the other color surface. Hence black color plastic bucket of 10 l capacities. Three sets of portable water heater are made i.e. (1) Non insulated, open plastic bucket (OPB), (2) Non-insulated plastic bucket, top surface covered with a transparent cover (CPB), (3) Insulated plastic bucket, closed with a transparent cover (ICPB). Schematic arrangement for the CPB along with the floating cover and immersion rod is Floating cover gives credence to the variation in volumetric mass water within the bucket. OPB, CPB, and ICPB are fed with the 10 l tab water and kept exposed to the incident solar radiation for four hours. K-type thermocouples and MDTI -027 temperature indicators are used for measuring and recording the temperature rise. Following observations are recorded:

- Water temperature rises within the OPB, CPB, and ICPB at 15 min interval.
- Ambient temperature.
- Potential difference (voltage) with the help of voltmeter.
• Current flowing through the immersion rod with the help of ammeter.

![Fig.1a](image1)

![Fig. 1b](image2)

3. Mathematical background

Three different configurations for the heating of water in a bucket by an electrical immersion rod are shown.

For mathematical evaluation of the system following assumptions are made:

a. Constant rate electric power supply.
b. Cylindrical shape of bucket.
c. Constant mass of water.
d. Uniform temperature bucket water.
e. Neglecting evaporative losses, covered bucket with transparent material.

The energy balance mathematical relation for the bucket containing water one can get:

\[ M_w C_w \frac{dT_w}{dt} = E_r - Q_r \]  

(1)

where, \( E_r = E_c + E_s \); \( Q_{net \ loss} = Q_c + Q_e + Q_r + Q_s + Q_B \)

\( E_r \) is the total power supplied to the water through solar radiation \( (E_c) \) and electrical immersion rod \( (E_e) \) in watts whereas \( Q_{net \ loss} \) is the energy loss through the conduction, evaporation, and radiation, through the top, lateral, and bottom surface [12].

Various losses may be given as follows:

\[ Q_c = h_c A_T (T_w - T_a) \]  

(2)

\[ Q_e = 0.013 h_e A_T (P_w - \gamma P_a) \]  

(3)

\[ Q_r = h_r A_T (T_w - T_a) \]  

(4)

\[ Q_s = h_s A_s (T_w - T_a) \]  

(5)

\[ Q_B = h_B A_B (T_w - T_a) \]  

(6)
Heat transfer coefficients one can get [13]:

\[ h_c = 5.7 + 3.8v \]  
\[ h_r = \frac{\varepsilon_{eff} \sigma \left[ (T_w + 273)^4 - (T_a + 273)^4 \right]}{T_w - T_a} \]

where, \( \sigma (= 5.67 \times 10^{-8} \text{ W/m}^2\text{K}^4) \) is Stefan’s constant, and a bar represents the average (throughout the heating process) of the quantity over it. Whereas, effective emissivity of the plate-glazing system, and can be written as:

\[ \frac{1}{\varepsilon_{eff}} = \left[ \frac{1}{\varepsilon_w} + \frac{1}{\varepsilon_a} - 1 \right]^{-1} \]

\[ h_s = \left[ \frac{1}{h_{ws}} + \sum_j \frac{2}{K_j r_j} \ln \left( \frac{r_{j+1}}{r_j} \right) + \frac{1}{h_b} \right]^{-1} \]

\[ h_B = \left[ \frac{1}{h_{ws}} + \sum_k \frac{L_k}{K_k} \right]^{-1} \]

where, \( j \) and \( k \) denote the numbers of layers of side and bottom of the bucket respectively. It has been observed that the evaporative heat transfer coefficient (\( h_e \)) has a nonlinear dependency on the temperature. The saturated vapor pressure for a narrow range of temperature variation can be represented by linear temperature dependence.

\[ P = R_1 T + R_2 \]

where, \( R_1 \) and \( R_2 \) are the constants evaluated using least squares curve fitting of saturation the vapor pressure for a longer range of interest and can be evaluated with the following relation.

\[ P_w = \exp \left( 25.317 - \frac{5144}{T_w + 273} \right) \]

\[ Q_e = 0.013 h_e \left[ R_1 (T_w - \gamma T_a) - R_2 (1 - \gamma) \right] \]

and

\[ \frac{dT_w}{dt} + \alpha T_w = \beta \]
where,  
\[ \alpha = \left[ (H_0 A_T + h_e A_e + h_b A_B) / M_w C_w \right] ; \]

\[ \beta = \left[ E_T + (H_1 A_T + h_e A_e + h_b A_B) T_a - 0.013 h_c A_T R_2 (1 - \gamma) \right] \frac{1}{M_w C_w} ; \]

\[ H_0 = (h_e + h_r + 0.013 h_c R_1) ; \]

and \( H_1 = (h_e + h_r + 0.013 h_c R_2) \)

From Eq. 15 at initial condition \( T_w = T_{w0} \) & \( t = 0 \) one can get:

\[ T_w = \frac{\beta}{\alpha} + \left( T_{w0} - \frac{\beta}{\alpha} \right) \exp(-\alpha t) \] (16)

In cooling mode \( (E = 0) \), from Eq.15 one can get:

\[ \frac{dT_w}{dt} = -\alpha (T_w - T_{\text{eff}}) \] (17)

where, \( T_{\text{eff}} = \left[ T_a - \frac{0.013 h_e A_T (1 - \gamma) (R T_a + R_2)}{M_w C_w \alpha} \right] \) (18)

solving Eq.17, one can get the expression for water temperature:

\[ T_w = T_{\text{eff}} + (T_{w0} - T_{\text{eff}}) \exp(-\alpha t) \] (19)

It is analogous to the Newton’s law of cooling; it can be observed that at zero heat loss \( T_{\text{eff}} \) reduces to \( T_a \). Using value of \( \alpha \) (loss coefficient) for typical set of data thermal performance of the system can be evaluated.

Other influencing parameters can be evaluated with the help of expressions written below.

i. Time taken to rise temperature of water from \( T_{w0} \) to \( T_{wf} \) can be obtained.

\[ T_H = \frac{1}{\alpha} \ln \left( \frac{T_{wf} - \beta / \alpha}{T_{w0} - \beta / \alpha} \right) \] (20)

ii. The efficiency of utilization of solar and electrical energy \( \eta \) one can get.

\[ \eta = \frac{M_w C_w (T_{wf} - T_{w0})}{\int_{t_0}^{t_f} E_s dt + \int_{t_{0s}}^{t_{fs}} E_s dt} \] (21)
4. Cost analysis

Total annual cost of the system can be expressed in response to corresponding initial investment as follows [14]:

\[ C_{TA} = C_B f_1 + C_H f_2 + C_E \int_0^{1 \text{ Year}} E_t \, dt \]  

(22)

where, \( f_1 \) and \( f_2 \) are the annuity factors, which can obtained:

\[ f_1 = \frac{q^L B (q - 1)}{q^L B - 1} \]  

(23)

\[ f_2 = \frac{q^L H (q - 1)}{q^L H - 1} \]  

(24)

where, \( q = \left(1 + \frac{Z}{100}\right) \)

Annual amount of useful energy (kWh) one can get:

\[ Q_u = \int_{\text{Year}}^{\text{Year}} M_w C_w (T_w - T_{w0}) \, dt \]  

(25)

The cost of 1 kWh of useful energy one can get:

\[ C_u = \frac{C_T}{C_u} \]  

(26)

5. Result and Discussion

All the experiments are carried out in the month of January, 2017 at Jaypee University of Engineering and Technology, Guna (24.4348° N, 77.1606° E). Maximum and minimum incident solar radiation on the horizontal surface has recorded 890 and 640 W/m² respectively during the experimentation. Variation in incident solar radiation has been recorded and shown in Fig. 2. At the beginning of the experimentation incident solar radiation have been recorded 792 W/m² which increase at 13:00 hour by 12.37%. After 13:00 hour it starts to decline and reduce by 28.09% at 14:45 hour while the experimentation.

At beginning of the experimentation OPC, CPB, and ICPB are filled with the cold water (10 l each) of temperature 22.8 °C and results obtained from experimentation and theoretical evaluation and its variation due to the incident solar radiation as a function of time is shown in Fig. 3. Maximum temperature rise after two hour time interval in OPB, CPB, and ICPB are 29.82%, 47.36%, and 21.49% respectively as compared with the initial value the temperatures (22.8 °C). Water temperature of the OPB, CPB, and ICPB are attained its highest value at 14.45
hour during the experimentation whereas as it results obtained from the theoretical models are slightly decreases after 14:00 hour due to reduction of an incident solar radiation.

**Fig. 2**

Water temperature raise in CPB has maintained its lead throughout the experimentation as compared with the OPB and ICPB, whereas ICPB lags behind as compared with OPB and CPB due to the lateral surface insulation. Temperature rise in OPB has moderate value as compared with the CPB and ICPB.

**Fig. 3**

Temperature gain by water within OPB and CPB due to the Bajaj Vacco (Immersion Water Heater Rod) of 1000 W capacity.

**Fig. 4**

The rise in temperature for both cases have been recorded at an interval of two minutes and represented with the help of Fig.4. Water within the CPB retains more heat as it is covered from the top surface which caused a temperature rise recorded in CPB maintain its lead as compared to the OPB throughout the heating process. Due to presence of top cover during water heating with the help of emersion rod time required to rise unit degree temperature is less as compared with the OPB is less and power consumption has reduced in CPB as compared with the OPB.

Eight sets (23-50°C, 24-50°C, 28-50°C, 30-50°C, 34-50°C, 36-50°C, 38-50°C, and 40-50°C) of experiment are carried out for analyzing the electrical power consumption in OPB and CPB during water heating with the help of electrical heater an obtained results during the experimentation are shown in Fig. 5.

**Fig. 5**

**Fig. 6**

Estimated cost saving on the basis of expected population growth by world health organization (WHO) has been represented with Fig.6 due to recorded and expected growth rate in the population of rural and urban areas.
Estimated saving from 2016 to 2022 on the basis of estimated population and 10% price hike on electricity have been represented with Fig. 7. Estimated Population growth has been recorded 2.13, 3.39, 5.74, 7.86, 9.63, and 11.4% higher in year from 2017 to 2022 as compared to population of 2016 whereas net saving due to utilization solar energy in CPB for a range of 35-50 °C is net saving increased by 12.34, 25.76, 40.73, 57.93, 76.45, 97.18% from 2017 to 2022 as compared to saving in 2016.

6. Conclusions

On the basis of experimental theoretical investigation following conclusions are drawn:

- Open bucket water heating with the help of immersion rod is inefficient process.
- Use of transparent plastic cover mater helps reducing electrical power consumption significantly.
- The transparent floating cover can also be a cost-effective solution for cost reduction.
- For dry climatic condition, the electrical heating system operates more uneconomically.
- Utilization of solar energy for heating of water will reduce electric power consumption significantly.
- For reducing heat loss higher power rating immersion rod can be used.

References


**Figure captions**

Fig.1a *Actual photograph of OPB, CPB, and ICPB.*

Fig. 1b: Schematic representation of CPB along with immersion rod and floating transparent cover.

Fig. 2: Variation of incident solar radiation with respect to time.

Fig. 3: Variation of bucket water temperature due to incident solar radiation with respect to time.

Fig. 4: Variation of water temperature in OPB and CPB due to immersion rod with respect to time.

Fig. 5: Variation of power consumption with respect to the temperature range.

Fig. 6: Variation of energy saving and estimated cost as per the domestic rate of MP India with respect to saved energy.

Fig. 7: Variation of estimated population growth of urban area by WHO and cost saving with respect to the concerned year.
Figures

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