Design and performance testing of a bread box type low cost solar water heater for rural area

Than Than Htike*, Mi Sandar Mon †, Saw Ba Tin#

*Department of Mechanical Engineering, Yangon Technological University, Yangon, Myanmar

†Department of Mechanical Engineering, Yangon Technological University, Yangon, Myanmar

#Department of Mechanical Engineering, Pyay Technological University, Pyay, Myanmar

E-mail: drthanthan.mech@gmail.com

Abstract. This paper deals with the design of integral passive low cost solar water heating system of "Bread Box" type for rural area. The designed capacity is 200lit and aims to cover the need of hot water at evening/night and morning for one to three people. This type of heater consists of horizontal cylindrical Mild-Steel tank painted flat black and is enclosed in a glazed (glass) insulated rectangular wooden box whose lid and front are opened as reflector (mercury-backed mirror) during the day and closed as insulation at night. In this research, bread box solar water heater was designed and constructed with local materials and then, this heater was tested. In this design, the diameter of collector-storage tank is 0.55 m, its length is 0.797 m and collector area is 1.377m². The total glazing area of this heater is 1.859 m² and box size is 1.341m x 0.884m x 0.76m.

1. Introduction
In developing nations, heating water for bathing and cooking is often the most expensive and time-consuming process in the household energy budget. And then, their traditional fuel sources such as wood, gas and electricity are unsustainable as they are costly to households and contribute to build up of greenhouse gases in the atmosphere. One potential solution to this problem is the use of low-cost residential solar water heater such as integral collector-storage (ICS) heater also called "Bread Box or Batch Solar Water Heater" for households used especially for the rural area. In which, at the winter time hot water is necessary for early morning and at night. By using the renewable energy, it can reduce electrical energy and hence, energy saving and cost saving as well.

The main objective of this paper is to design, construct with locally available material and test the "Bread Box" type low cost solar water heater for hygiene and health and to contribute global climate protection by using small-scale renewable energy application.

2. Solar radiation
In designing solar energy systems, it is usually necessary to go beyond basic ideas to more advanced concepts in the science of heat energy. This section is devoted to discussion of solar radiation, the
energy that arrives at the earth’s surface from the sun. Total solar radiation intensity (insolation) received on a surface is illustrated as shown in Figure 1.

![Illustration of the solar radiation intensity](image)

**Figure 1.** Illustration of the solar radiation intensity [1]

### 2.1. Direct and diffuse solar radiation

The intensity of solar radiation that is available on the surface of the earth depends on reflection of the atmosphere and the earth's outer surface, scattering in the earth's atmosphere and absorption by the atmosphere. The solar radiation intensity on the surface of the earth’s;

\[
I_{DN} = [G_{o,H} + G_{o,V}] \bar{K}_T
\]  

Where, 
- \( I_{DN} \) = Direct beam solar radiation intensity 
- \( G_{o,H} \) = Extraterrestrial radiation onto a horizontal surface 
- \( G_{o,V} \) = Extraterrestrial radiation onto a vertical surface 
- \( \bar{K}_T \) = Mean daily clearness index 

Diffuse solar radiation intensity is calculated by:

\[
\frac{I_d}{I_{DN,\text{avg}}} = 0.175, \text{ (for } \bar{K}_T \geq 0.722 \text{ and } \omega_s \geq 81.4) \]  

Where, 
- \( I_d \) = Diffuse solar radiation intensity 
- \( I_{DN,\text{avg}} \) = Average direct beam solar radiation intensity (daily) 
- \( \bar{K}_T \) = Mean daily clearness index, 
- \( \omega_s \) = sunset hour angle

### 2.2. Reflected short-wave solar radiation

The amount of solar radiation reflected from the reflector onto a surface can be calculated by equation 3 [2].

\[
I_r = (I_{DN} + I_d) \times \rho_s \times F_{vf}
\]  

Where, 
- \( \rho_s \) = Reflectivity of a surface 
- \( F_{vf} \) = View factor from the reflector

### 2.3. Total solar radiation

The total solar radiation intensity is the sum of the direct beam solar radiation intensity (\( I_{DN} \)) and diffuse radiation (\( I_d \)) and reflected radiation (\( I_r \)) from the external reflectors.
The design data are based on 25th December, 2017 and the day length is from 8:00 AM to 4:00 PM. In this paper, the solar radiation intensity is calculated by using equation 1 to 4. The calculated hourly total solar radiation intensity is shown in Figure 2. The calculated available solar energy is \( Q_{\text{solar}} \) is 48.558 MJ/m\(^2\).

\[
I_{\text{Total}} = I_{\text{DN}} + I_d + I_r
\]  

(4)

Figure 2. Variation of hourly total solar radiation intensity

2.4. Average transmittance of glass cover

In solar applications, the transmission of radiation is through a slab or film of material. Transmittance of a single glass cover is allowed for both reflection and absorption losses. For the average transmittance of the two components is calculated by equation 5 [4].

\[
\tau = \frac{\tau_a}{2} \left[ \frac{1}{1 + \tau_a} x \frac{1 - \tau_a^2}{1 - \tau_a x \tau} \right] + \left[ \frac{1 - \tau_{II}^2}{1 + \tau_{II}} \right] \]  

(5)

Where,

\( \tau_a \) = Absorption losses

\( K \) = The extinction coefficient

\( \tau_\perp \) = Perpendicular component of polarized radiation

\( \tau_{II} \) = Parallel component of unpolarized radiation

Transmittance of the glass cover can be calculated by using equation 5 [4]. The variation of hourly average transmittance of glass cover is shown in Figure 3.
3. Design of Bread Box solar water heater

This paper aims to design "Bread Box" solar water heater. Design is considered for households use of two persons per day. The capacity of the heater is 200 litre. The source water temperature is 25 °C and expected maximum design temperature is 70 °C. This heater is designed as shown in Figure 4.

![Figure 4. Bread box solar water heater](image)

It consists of a single cylindrical storage mild-steel tank with painted flat black to absorb heat from the sun and then transfer to water stored within, thus, it do dual operation as collector-storage. The collector-storage tank is placed horizontally in an insulated rectangular wooden box to reduce heat loss and its lid and front are opened to collect sufficient solar radiation. Both apertures are covered with glazing material (glass) that is allowed to transmit short-wave solar radiation through glass and prevented long-wave thermal radiation came back from collector as convection and radiation losses. Two insulated externals reflectors (outside surface is made with wood and inside is mercury back mirror) are installed at lid and front of box. These two reflectors are opened at morning and closed at evening. They offer the advantages of increasing collector area (increasing solar gain), and then they can reduce night time heat loss, maintain higher temperatures through the night and protect heater overheat at noon time by closing reflectors. A bread box heater (integral passive solar water heater), allows cold water to flow in from the bottom of the tank and hot water to flow out of the top.

3.1. Design parameter

The design calculation is made by using the following design parameters.

![Figure 3. Variation of hourly average transmittance of glass cover.](image)
Localities
Locality = PYAY (height 31.4 m above sea level)
Latitude, l = 18° 48’ 0” N (18.8° N)
Longitude, LL = 95° 13’ 0” E (95.217° E)
Design time = 25th December, 2017 from 8:00 AM to 4:00 PM

3.2. Required energy
The total required energy to heat the water can be calculated by using equation 6 and 7.

\[ Q_w = m C_w \Delta T \]  
\[ = \rho V C_w (T_{set} - T_{source}) \]

Where, \( C_w \) = Specific heat capacity of water, 4.187 kJ/kg °C
\( \rho \) = Density of water, 1000 kg/m³
The parameters for water heating which are to be considered are:

i. Volume of water, \( V \) (m³) required in a given time period
ii. The temperature of the cold water
iii. Require delivery temperature

3.3. Sizing of collector/storage tank design
Available solar energy/area is calculated with equation 8 [5].

\[ Q_{input} = Q_{solar} \times \bar{\tau} \alpha \]  
\[ = \rho V C_w (T_{set} - T_{source}) \] / Time Taken

Where,
\( \tau \) = Average Transmittance of glass cover, 0.78
\( \alpha \) = Absorptance of collector, 0.56 [5]

Capacity of water, \( V = \pi/4 D^2 L \)
Length of tank, \( L = 4V/\pi D^2 \)  
\( = (4 \times 200 \times 10^{-3})/\pi D^2 \)
Collector area, \( A_c = \pi D L \)

Note
1. All surface area of tank absorbed energy equally.
2. To simplify the calculation, authors assume that energy losses are not significant.

3.4. Glazing area or aperture area design
The glazing must be adequately large and well enough insulated to collect sufficient solar radiation.

\[ A_g/surface \geq A_c/2 \text{(as glazing have two surfaces)} \]
\[ L \times W \geq A_c/2 \]  
where, \( L \) = Length of glazing
\( W \) = Width of glazing

3.5. Calculation of water tank delivery temperature
The temperature rise of water tank delivery temperature (Table 1) can be obtained by using equation 13 and 14. By calculation result, the maximum desire temperature is 71°C at 1:00 PM.

\[ Q_{solar} \times \bar{\tau} \alpha \times A_c = Q_w/\text{Time Taken} \]  
\[ = [\rho V C_w (T_{set} - T_{source})]/\text{Time Taken} \]
Table 1. Calculated results of the water tank temperature

| Time of Day (hours) | Water Tank Delivery Temperature (°C) |
|--------------------|-------------------------------------|
| 8:00 AM            | 28.26°C                             |
| 9:00 AM            | 34.54°C                             |
| 10:00 AM           | 43.03°C                             |
| 11:00 AM           | 52.94°C                             |
| 12:00 PM           | 62.65°C                             |
| 1:00 PM            | 71.04°C                             |

3.6. Calculated results for Bread Box solar water heater
This research is designed to heat 200 litres water from 25°C to 70°C. The design month is based on 25th December, 2017 and the day length is from 8:00 AM to 4:00 PM. Firstly, the direct-beam solar radiation, diffuse solar radiation and reflected short-wave solar radiation intensity are calculated. The results of total direct-beam solar radiation intensity is shown in Figure 2. Then, the required energy to heat water can be calculated by using equation 6 and 7. Transmittance of the glass cover is also calculated. Then the required collector area can be obtained. Then the required collector area can be obtained. After that collector area, size of collector/storage tank, glazing area and size of insulated box are designed.

For the desire capacity 200 litres, the various sets of diameter, length and area of collector/storage tank and glazing can be obtained according to the equation 10 to 12. From these values, the diameter, length and collector area of tank is chosen to satisfy the required collector area. The calculated results for bread box solar water heater is as shown in table 2.

From these results, the collector area 1.377 m² and the glazing area 1.858 m² are satisfied with Rule of Thumb [6].

Table 2. Detailed dimension of a Bread Box solar water heater

| Components   | Materials                  | Dimensions                      |
|--------------|----------------------------|---------------------------------|
| Collector    | Mild-Steel Tank (50 gallon) | Diameter: 0.55 m, Length: 0.797 m, Area: 1.377 m² |
| Glazing      | Window Glass (0.0023m thick) | Length: 1.2192 m, Width: 0.76 m, Area: 1.858 m² (two sides) |
| Reflector    | Mirror (mercury backed)    | Length: 1.2192 m, Width: 0.76 m, Area: 1.858 m² (two reflectors) |
| Insulated Box| Wood, Sawdust              | Length: 1.341 m, Width: 0.884 m, Height: 0.76 m |

4. Fabrication of a Bread Box solar water heater
By using the above calculated results from table 2, the bread box solar water heater is constructed with locally available materials. The following materials are used in fabricating a bread box solar water heater:
Mild-Steel Tank (200 lit capacity) with urethane interior coating (heated water is for domestic use, not for drinking), Flat-Black Paint, GI Pipes, Copper or CPVC Pipes, Sockets and Valves, Wood, Sawdust, Window Glass, Mercury-Backed Mirrors (Reflectors) and Tools.
Fabrication is done by the following procedure.
Step 1: Wash the inside surface of Mild-Steel tank with mixture of caustic, detergent and water by rolling three or more time and then, cleaning and unrusting the outer (exterior) surface of the tank by using hand-grinder with abrasive paper, shown in Figure 5. Check water leakage of the tank.

![Cleaning Inside and outside surface of tank](image1)

**Figure 5.** Cleaning Inside and outside surface of tank

Step 2: After the tank have been cleaned, dry the tank and then, paint the exterior surface of tank with a flat-black paint

Step 3: Drill inlet hole at the bottom and outlet hole at the two-third of the collector-storage tank (Figure 6). And then, drill the drain hole and air vent at the bottom and at the top of the collector-storage tank, shown in Figure 6. After that, weld copper pipes at the inlet, outlet and drain holes by using welding machine. Check water leakage at these joint (of welding).

![Drilling and Pluming](image2)

**Figure 6.** Drilling and Pluming

Step 4: Construct insulated rectangular wooden box as shown in Figure 7 (a), with required dimensions. The front and lid of this insulated box are opened to cover with glazing. Fill inside surface of this box with sawdust at the bottom, back and side (left and right) and recover with wooden of this (sawdust) filling, shown in Figure 7 (b). And then, paint inside surface of this box with metallic shiny coating
Step 5: Place collector-storage tank (horizontally) in the insulated rectangular wooden box. And then, cover with window glass at the lid and front of this box. Check corners and joints of this box to prevent thermal losses. Construct reflectors with the dimension of the glazing and then, install at the lid and front of the box.

Step 6: After passing through step 1 to 5, construction of bread box solar water heater was finished.

5. Performance testing of a fabricated Bread Box solar water heater
To construct this bread box solar water heater, it took over one week. After the heater has been constructed, performance test was conducted in Pyay Technological University campus. To test this heater, firstly, it is necessary to look for south facing sunny spot. Then, cold water is filled from the bottom of the collector-storage tank and its reflectors are opened at morning time (sunrise) and closed at evening time (sunset), shown in Figure 8 (a) and (b).

The hot water temperature of this constructed heater are measured with three layers such that maximum temperature \((T_{\text{maximum}})\) from the top of the tank or air vent, delivery temperature \((T_{\text{delivery}})\) from outlet pipe and bottom temperature \((T_{\text{bottom}})\) from the inlet pipe and then, the ambient-water temperature is measured from the surrounding. The average results of tested water temperature from 1\(^{st}\) November to 8\(^{th}\) November, 2017 are shown in Figure 9.
According to the tested results of this bread box solar water heater, the maximum design temperature 70 °C of hot water reached at 12 noon and then, this maximum temperature was lowered to 40 °C at 7 o'clock (AM) after passing through night.

6. Cost analysis of a Bread Box solar water heater
The cost when the unit is manufactured commercially is about (150,000 MMK) and its expected life is about 20 years. When using electric power for heating 200 litre of water up to 70°C when the inlet temperature of water is 25°C, the energy required is 37.683 MJ.

One unit of electricity = 1KWh (3.6 MJ)
37.683 MJ = 10.47 KWh

It means that this amount of energy must put into the water. Therefore, for heating 200 litres of water through 45°C requires 1 KW rated electric immersion heated running for nearly 10 hours daily, which cost is about (263 MMK)/day or (7,875 MMK)/month or (94,500 MMK)/year. Therefore, the payback period for the solar water heater is only about one and a half year.

7. Conclusion
Renewable energy includes hydropower, solar energy, wind energy, wave energy and tidal energy. Like other renewable energy systems, solar water heater minimizes the environmental impacts of enjoying a comfortable, modern lifestyle. Solar water heater helps to reduce our dependence on imported fuel.

This bread box solar water heater would be provided numerous benefits to households for rural area. Many households could reduce their fuel costs by eliminating or reducing their need for wood, gas or electricity to heat water and also could improve their health and hygiene because of their low cost, ease of installation, durability and reliability.

The designed solar water heater costs around (150,000 MMK) and it saves about 10 KWh of energy per day and payback period of the heater is just over one year. It expected life is about 20 years and therefore it saves large amount of energy and households’ energy budgeted.

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