1. Introduction: A solar water heater is a combination of a solar collector array, an energy transfer system, and a storage tank. The main part of a solar water heater is the solar collector array, which absorbs solar radiation and converts it to heat. This heat is then absorbed by a heat transfer fluid (water, non-freezing liquid, or air) that passes through the collector. This heat can then be stored or used directly. Because it is understood that portions of the solar energy system are exposed to weather conditions, they must be protected from freezing and overheating caused by high insolation levels during periods of low energy demand. Two types of solar water heating systems are available:

- Direct or open loop systems, in which potable water is heated directly in the collector.
- Indirect or closed loop systems, in which potable water is heated indirectly by a heat transfer fluid that is heated in the collector and passes through a heat exchanger to transfer its heat to the domestic or service water.

Systems differ also with respect to the way the heat transfer fluid is transported:

- Natural (or passive) circulation systems [no pump is employed to circulate the fluid].
- Forced circulation (or active) systems [a pump or fan is employed to circulate the fluid].

A wide range of collectors have been used for solar water heating systems, such as flat plate, evacuated tube, and compound parabolic. In addition to these types of collectors, bigger systems can use more advanced types, such as the parabolic trough.
The amount of hot water produced by a solar water heater depends on the type and size of the system, the amount of sunshine available at the site, and the seasonal hot water demand pattern.

2. Passive Systems: Two types of systems belong to this category: **thermosiphon** and the **integrated collector storage systems**.

2.1 Thermosiphon Systems:
Thermosiphon systems, shown schematically in Figure (1), heat potable water or transfer fluid and use natural convection to transport it from the collector to storage. The thermosiphoning effect occurs because the density of water drops with the increase of the temperature. Therefore, by the action of solar radiation absorbed, the water in the collector is heated and thus expands, becoming less dense, and rises through the collector into the top of the storage tank.

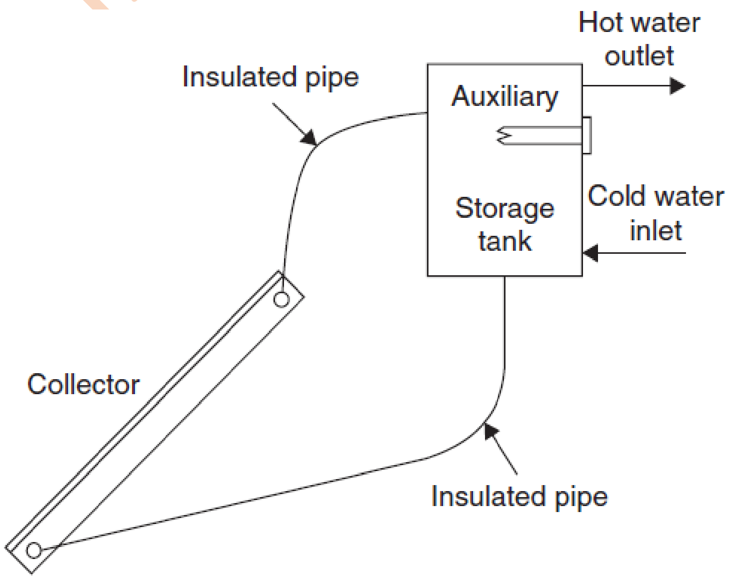

Fig (1): Schematic diagram of a thermosiphon solar water heater.

There it is replaced by the cooler water that has sunk to the bottom of the tank, from which it flows down the collector. Circulation is continuous as long as the sun is shining. Since the driving force is only a small density difference, larger than normal pipe sizes must be used to minimize pipe friction. Connecting lines must also be well insulated to prevent heat loss and sloped to prevent formation of air pockets, which would stop circulation.
The advantages of thermosiphon systems are that they do not rely on pumps and controllers, are more reliable, and have a longer life than forced circulation systems. Moreover, they do not require an electrical supply to operate and they naturally modulate the circulation flow rate in phase with the radiation levels. The main disadvantage of thermosiphon systems is that they are comparatively tall units, which makes them not very attractive aesthetically.

2.1.1. Theoretical Performance of Thermosiphon Solar Water Heaters:

The collector thermal performance can be modeled by dividing it into (N_c) equally sized nodes. The temperature at the midpoint of any collector mode (k) is given by

$$T_k = T_a + \frac{I_t\, F_R\, (\tau\alpha)}{F_R\, U_L} + \left[T_i - T_a - \frac{I_t\, F_R\, (\tau\alpha)}{F_R\, U_L}\right] exp\left[-\frac{F'\, U_L\, A_c}{\dot{m}_t\, c_p} \times \frac{(k-(1/2))}{N_c}\right] \dots (1)$$

$\dot{\boldsymbol{m}}_{\boldsymbol{t}}$ Thermosiphonic flow rate (kg/s). $\boldsymbol{A_c}$ Collector area (m^2).

The collector parameter, $(F'\, U_L)$, is calculated from the collector test data for $(F_R\, U_L)$ at test flow rate $(\dot{m}_T)$ by

$$F'\, U_L = \frac{-\,\dot{m}_T\, c_p}{A_c} \ln\left[1 - \frac{F_R\, U_L\, A_c}{\dot{m}_T\, c_p}\right] \dots (2)$$

Finally, the useful energy from the collector is obtained from

$$Q_u = r\, A_c\, [\, F_R\, (\tau\alpha)\, I_t - F_R\, U_L (T_i - T_a)] \dots (3)$$

$$r = \frac{F_R\, \dot{m}_t}{F_R\, \dot{m}_T} = \frac{\dot{m}_t\left[1-exp\left(-\frac{F'\, U_L\, A_c}{\dot{m}_t\, c_p}\right)\right]}{\dot{m}_T\left[1-exp\left(-\frac{F'\, U_L\, A_c}{\dot{m}_T\, c_p}\right)\right]} \dots (4)$$

The temperature drop along the collector inlet and outlet pipes is usually very small (short distance, insulated pipes), and the pipes are considered to be single nodes, with negligible thermal capacitance. The first-law analysis gives the following expressions for the outlet temperature (T_{po}) of pipes:

$$T_{po} = T_a + \left(T_{pi} - T_a\right) exp\left[-\frac{(UA)_p}{\dot{m}_t\, c_p}\right] \dots (5)$$

The friction head loss in pipes is given by

$$H_f = \frac{fLv^2}{2d} + \frac{kv^2}{2} \dots (6)$$

$\boldsymbol{d}$ = Pipe diameter (m).
$\boldsymbol{L}$ = Length of pipe (m).
$\boldsymbol{f}$ = Friction factor.
$\boldsymbol{v}$ = Fluid velocity (m/s).
k = Friction head (m).

The friction factor, *f*, is equal to

$$f = 64/Re \text{ For } [Re < 2000] \ldots (7)$$

$$f = 0.032 \text{ For } [Re > 2000] \ldots (8)$$

Table 1. Friction Head of Various Parts of the Thermosiphon Circuit.

Parameter	*k* Value
Entry from tank to connecting pipe to collector	0.5
Losses due to bends in connecting pipes	
Right-angle bend	Equivalent length of pipe increased by 30*d* for Re ≤ 2000 or *k* = 1.0 for Re ≥ 2000
45° bend	Equivalent length of pipe increased by 20*d* for Re ≤ 2000 or *k* = 0.6 for Re > 2000
Cross-section change at junction of connecting pipes and header	
Sudden expansion	$k = 0.667(d_1/d_2)^4 - 2.667\,(d_1/d_2)^2 + 2.0$
Sudden contraction	$k = -0.3259(d_2/d_1)^4 - 0.1784\,(d_2/d_1)^2 + 0.5$
Entry of flow into tank	1.0

Note: For pipe diameters, d_1 = inlet diameter and d_2 = outlet diameter.

The friction factor for the developing flow in the connecting pipes and collector risers is given by

$$f = 1 + \frac{0.038}{\left(\frac{L}{d\,Re}\right)^{0.964}} \ldots (9)$$

The collector header pressure drop, (P_h), is equal to the average of pressure change along inlet and outlet headers for equal mass flow in each riser, given by

$$S_1 = \sum_{i=1}^{N} \frac{N-i+1}{N^2} \ldots (10)$$

$$S_2 = \sum_{i=1}^{N} \frac{(N-i+1)^2}{N^2} \ldots (11)$$

$$A_1 = \frac{f L_h v_h^2}{2 d_h} \ldots (12)$$

Where, from Eq. (7), $f = 64/Re$ (Re based on inlet header velocity and temperature) and

If $\boldsymbol{f = 64/Re} \rightarrow$ $\quad$ $\boldsymbol{A_2 = A_1} \ldots (13)$

Based on the outlet header velocity and temperature,

$$A_2 = (\rho\, v_h^2/2) \ldots (14)$$

Finally,

$$P_h = \frac{-S_1 A_1 + 2(S_2 A_3) + S_1 A_2}{2} \ldots (15)$$

3. Active Systems:

In active systems, water or a heat transfer fluid is pumped through the collectors. These are usually more expensive and a little less efficient than passive systems. Additionally, active systems are more difficult to modify in houses, especially where there is no basement, because space is required for the additional equipment, such as the hot water cylinder. Five types of systems belong in this category: ***direct circulation systems***, ***indirect water heating systems***, ***air systems, heat pump systems, and pool heating systems***.

3.5. Solar Pool Heating Systems:

A. Evaporation Heat Loss:

The evaporative heat loss from a still outdoor pool is a function of the wind speed and of the vapor pressure difference between the pool water and the atmosphere, given by

$$q_e = (5.64 + 5.96\, v_{0.3})(P_w - P_a) \; \ldots (16)$$

$\boldsymbol{q_e}$ = Heat loss by evaporation (MJ/m^2 -d).

$\boldsymbol{P_w}$ = Saturation water vapor pressure at water temperature, $\boldsymbol{t_w}$ (kPa).

$\boldsymbol{P_a}$ = Partial water vapor pressure in the air (kPa).

$v_{0.3}$ = Wind speed velocity at a height of 0.3 m above the pool (m/s).

Usually, the wind speed is measured at 10 m from the ground (v_{10}); therefore,

For normal suburban sites, $\boldsymbol{v = 0.30\, v_{10}}$ … (17)

For well-sheltered sites, $v = 0.15\, v_{10}$ … (18)

For indoor pools, the low air velocity results in a lower evaporation rate than usually occurs in outdoor pools, and the evaporative heat loss is given by

$$q_e = (5.64 + 5.96\, v_s)(P_w - P_{enc}) \; \ldots (19)$$

$\boldsymbol{P_{enc}}$ = The partial water vapor pressure in the pool enclosure (kPa).
$\boldsymbol{v_s}$ = Air speed at the pool water surface, typically 0.02 – 0.05 (m/s).

Partial water vapor pressure (P_a) can be calculated from the relative humidity (RH),

$$P_a = \langle (P_s \times RH)/100 \rangle \; \ldots (20)$$

P_s = Saturation water vapor pressure at air temperature, t_a (kPa).

Saturation water vapor pressure can be obtained from

$$P_s = 100(0.004516 + 0.0007178\, t_a - 2.649 \times 10^{-6}\, t_a^2 + 6.944 \times 10^{-7}\, t_a^3) \; \ldots (21)$$

B. Radiation Heat Loss:

Radiation heat loss is given by

$$q_r = \frac{24 \times 3600}{10^{-6}}\, \varepsilon_w\, \sigma(T_w^4 - T_s^4) = 0.0864\, \varepsilon_w\, h_r\, (T_w - T_s) \; \ldots (22)$$

$\boldsymbol{q_r}$ = Radiation heat loss (MJ/m² -d).
$\boldsymbol{T_w}$ = Water temperature (K).
$\boldsymbol{h_r}$ = Radiation heat transfer coefficient (W/m² -K).
$\boldsymbol{\varepsilon_w}$ = Long wave emissivity of water = 0.95.
T_s = Sky temperature (K).

The radiation heat transfer coefficient is calculated from

$$h_r = \sigma(T_w^2 + T_s^2)(T_w + T_s) \approx 0.268 \times 10^{-7} \left[\frac{T_w + T_s}{2}\right]^3 \ldots (23)$$

For an indoor pool, $T_s = T_{enc}$ both in Kelvins, and T_{enc} is the temperature of the walls of the pool enclosure.
For an outdoor pool,

$$T_s = T_a\sqrt{\varepsilon_s} \ldots (24)$$

Where sky emissivity, ε_s , is a function of dew point temperature, t_{dp} , given by

$$\varepsilon_s = 0.711 + 0.56\left[\frac{t_{dp}}{100}\right] + 0.73\left[\frac{t_{dp}}{100}\right]^2 \ldots (25)$$

for cloudy skies → $\boldsymbol{T_s \approx T_a}$ … (26)
for clear skies → $T_s \approx T_a - 20$ … (27)

C. Convection Heat Loss:

Heat loss due to convection to ambient air is given by

$$q_c = \frac{24 \times 3600}{10^{-6}}\,(3.1 + 4.1\,v)(t_w - t_a) = 0.0864\,(3.1 + 4.1\,v)(t_w - t_a) \ldots (28)$$

$\boldsymbol{q_c}$ = Convection heat loss to ambient air (MJ/m^2 -d).
$\boldsymbol{v}$ = Wind velocity at 0.3 m above outdoor pools or over the pool surface for indoor pools (m/s).
$\boldsymbol{t_w}$ = Water temperature (℃).
t_a = Air temperature (℃).

D. Make-Up Water:

If the make-up water temperature is different from the pool operating temperature, there will be a heat loss, given by

$$q_{muw} = m_{evp}\, c_p\, (t_{muw} - t_w) \ldots (29)$$

$\boldsymbol{q_{muw}}$ = Make-up water heat loss (MJ/m^2-d).
$\boldsymbol{t_{muw}}$ = Temperature of make-up water (℃).
$\boldsymbol{m_{evp}}$ = Daily evaporation rate (kg/m^2-d).
c_p = Specific c heat of water (J/kg-℃).

The daily evaporation rate is given by

$$m_{evp} = \left(q_c / h_{fg}\right) \ldots (30)$$

Where h_{fg} = latent heat of vaporization of water (MJ/kg).

E. Solar Radiation Heat Gain:

Heat gain due to the absorption of solar radiation by the pool is given by

$$q_s = \alpha\, H_t \;\ldots (31)$$

$\boldsymbol{q_s}$ = Rate of solar radiation absorption by the pool (MJ/m^2-d).

$\boldsymbol{H_t}$ = Solar irradiation on a horizontal surface (MJ/m^2-d).

$\boldsymbol{\alpha}$ = Solar absorptance (α = 0.85 for light-colored pools; α = 0.90 for dark colored pools).

Ex: A 500 m^2 light-colored swimming pool is located in a normal suburban site, where the measured wind speed at 10 m height is 3 m/s. The water temperature is 25 °C, the ambient air temperature is 17 °C, and relative humidity is 60%. There are no swimmers in the pool, the temperature of the make-up water is 22 °C, and the solar irradiation on a horizontal surface for the day is 20.2 MJ/m^2-d. How much energy must the solar system supply (Q_{ss}) to the pool to keep its temperature to 25 °C?

Solution

The energy balance of the pool is given by

$$q_e + q_r + q_c + q_{muw} - q_s = q_{ss}$$

The velocity at 0.3 m above the pool surface is $0.3 \times 3 = 0.9\ m/s$.

The saturation water vapor pressure at air temperature t_a is also given by

$$P_s = 100(0.004516 + 0.0007178\, t_a - 2.649 \times 10^{-6}\, t_a^2 + 6.944 \times 10^{-7}\, t_a^3)$$

$$P_s = 100(0.004516 + 0.0007178 \times 17 - 2.649 \times 10^{-6} \times 17^2 + 6.944 \times 10^{-7} \times 17^3)$$

$$P_s = 1.936\ kPa$$

$$P_a = \langle (P_s \times RH)/100 \rangle = \langle (1.936_s \times 60)/100 \rangle = 1.162\ kPa$$

Saturation water vapor pressure can also be obtained from Eq. (21) by using t_w instead of t_a

$$P_s = 3.166 kPa$$

$$q_e = (5.64 + 5.96\, v_{0.3})(P_w - P_a) = (5.64 + 5.96 \times 0.9)(3.166 - 1.162) = 22.052\ MJ/m^2 - d$$

$$\varepsilon_s = 0.711 + 0.56\left[\frac{t_{dp}}{100}\right] + 0.73\left[\frac{t_{dp}}{100}\right]^2 = 0.711 + 0.56\left[\frac{17}{100}\right] + 0.73\left[\frac{17}{100}\right]^2 = 0.827$$

$$T_s = T_a\sqrt{\varepsilon_s} = 290\sqrt{0.827} = 263.7\ K$$

$$q_r = \frac{24 \times 3600}{10^{-6}}\, \varepsilon_w\, \sigma(T_w^4 - T_s^4) = 0.0864 \times 0.95 \times 5.67 \times 10^{-8}\,(298^4 - 263.7^4)$$
$$= 14.198\ MJ/m^2 - d$$

$$q_c = 0.0864\,(3.1 + 4.1\, v)(t_w - t_a) = 0.0864\,(3.1 + 4.1 \times 0.9)(25 - 17) = 4.693\ MJ/m^2 - d$$

From steam tables, h_{fg} the latent heat of vaporization of water at 25 °C is equal to 2441.8 kJ/kg. Therefore, the daily evaporation rate is given by

$$m_{evp} = \left(q_c/h_{fg}\right) = (4.693\ \times 10^3/2441.8) = 1.922\ kg/m^2 - d$$

$$q_{muw} = m_{evp}\ c_p\ (t_{muw} - t_w) = 1.922 \times 4.18(22 - 25) = 24.10\ MJ/m^2 - d$$

The negative sign is not used, because all the values are losses.

The solar radiation heat gain is

$$q_s = \alpha\ H_t = 0.85 \times 20.2 = 17.17\ MJ/m^2 - d$$

Therefore, the energy required by the solar system to keep the pool at 25 °C is

$$q_{ss} = q_e + q_r + q_c + q_{muw} - q_s$$

$$q_{ss} = 22.052 + 14.198 + 4.693 + 24.1 - 17.17 = 47.873\ MJ/m^2 - d$$

$$Q_{ss} = 23.94\ GJ/d$$