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A new design of solar water heater

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Abstract. This investigation presents a new design of solar water heater as a pyramid shaped frustum. The proposed design is a compact system in which collectors and a water storage tank are integrated together into one unit. The concept of using the frustum of pyramid as an external shape for collecting the solar radiation and as a container for hot water storage tank are presented. The frustum of pyramid solar water heater has five surfaces, four surfaces represent liquid flat-plate collectors as roof and three sides which received all the solar radiation incidént on them. The roof and one of the sides face the south direction but the other sides face the south-east and south-west directions, repectively. The three sides tilted the horizontal plane to 30° while the roof tilted to 15°. The total surface area of the collectors is about of 1·68 m^2 and the capacity of the water storage tank is about 150 litres. The absorber consists of copper tubes formed in a serpentine shape which are connected to the tank by two openings (inlet and outlet). A regulator is connected to the piping line to control the hot water consumption and the reverse flow after sunset. The thermal analysis of the liquid flat-plate collector and the performance of the solar water heater are derived based on the steady state analysis. A comparison between the compact unit and another type which has an elevated tank is done. The results show that the proposed solar water heater gives good performance and can provide a quantity of hot water of about 175 litres/day at an average temperature range from 40°–60°C depending on the weathering conditions and solar intensity.

Keywords. Compact unit-liquid flat-plate collector; solar energy; thermal analysis; water heating.

1. Introduction

A traditional and wide-spread use of solar energy is heating. The most widely promoted application in Egypt during the past decade has been solar water heater which represents the largest solar heating industries. The industrial design generally deals with all product requirements or problems related to function, construction and appearance [1]. The successful design is the one which satisfies many parameters. In the case of solar water heater as a solar energy product, the functional parameters have received considerable attention [2–4], where the efficiency of the solar device was the main concern of the designer. On the other hand, the appearance received very limited consideration from solar energy scientists and technologists. Therefore, the present study concentrates on the design aspects that lead to a more elegant appearance.

A study on the results of the solar energy calculations are needed to design a new integrated system. These results may be able to calculate exactly the size, shape, structure, performance measures and efficiency. The temperature distribution in the flat-plate solar collectors using the finite elements method and assessment of novel flat-plate solar collectors compared by to the conventional design are investigated by El-Haggar [5,6]. The determination of the long-term thermal performance of natural circulation solar energy water heater is studied by Zerrouki [7]. Thermal optimization of compact solar water heater is carried out by [8].

The present study is concerned with a new design of solar water heater in the shape of a pyramidical frustum which is the best shape to collect the maximum amount of solar radiation during day and all over the year, if the proper angles of its surfaces are used.

2. Constructional design

Nature creates forms and structures according to the requirements of minimum energy. The procedure of a successful solar design should take into consideration both time and space as individual design factors. The time data of constructing a solar envelope is perceived from the movement of the sun from one region to another. This movement is defined by a daily path, from east in the morning to west in the afternoon, and by a seasonal path, from south in winter to north in summer. These apparent solar migrations by day and season describe the boundaries of the solar envelope and therefore limits of development within. Egypt extends from 22°N and 31·5°N and enjoys 3000 to 4000 sunshine hours per year and the solar energy has a high potential, specially in the southern regions.

Shape and structure respond to seasonal variations by opening up to the south when possible. A cube-like form orientation will receive different amounts of solar energy from one face to another. Different grouping of forms influence their relative exposure to solar radiation. Compact forms expose less surface area to the sun than expansive ones, and the roof in usually the surface most exposed to the sun [9]. The solar water heater usuallly has a conventional flat-plate collector, which is set at an angle to receive the maximum radiation on an average all round year.

The proposed solar water heater consists of two concentric frustums of pyramids as shown in figures 1 and 2. The outer one represents the transparent glass cover as a conventional solar flat-plate collector. The inner one represents the hot water storage tank. It is insulated by glass wool of proper thickness. The outer faces of the storage tank are convered by black coated tubes (Sinusoidal) which represent the solar absorber. The gap between the two concentric frustums of pyramids may be evacuated to minimize the heat losses to the surroundings. Cold water is fed to the tubes to heated and then introduced to the storage tank. The absorber tubes absorb all the incident solar radiation passing through the glass cover. A new solar water heater has five surfaces at different site angles. They are the best angles through the four seasons. One of the surfaces represents the roof and other surfaces represent the sides of the heater with all surfaces being of trapezoidal shape. The amount of solar radiation obtained by the proposed solar water heater is evaluated to be higher than the conventional solar water heater.

The proposed solar water heater sits at an angle which receives the maximum amount of solar radiation on an average all through the year. This angle is of course not the best at any time. The proposed shape as an integrated system can achieve: (i) Frustum of pyramid form has a low centre of gravity and structures would be entirely self-supporting which provide stability in an open area, (ii) trapezoidal shape of solar collector replaced by the flat-plate shape improves appearance and performance at the same time, (iii) increase in the space of energy radiation cycle all the year, and

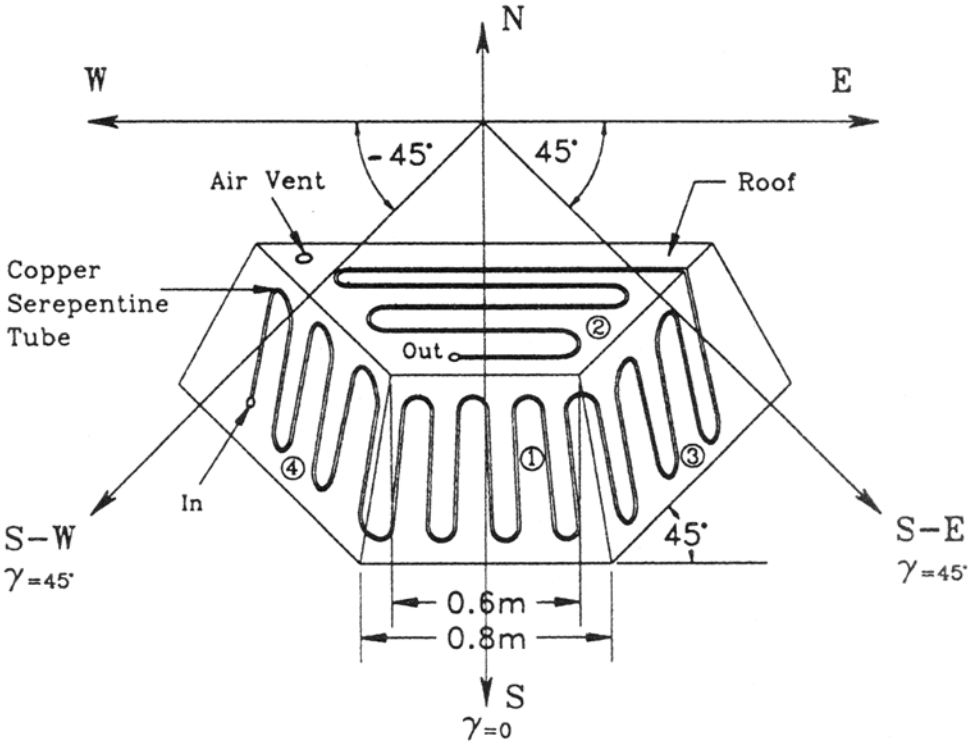

Figure 1. The position of the collectors

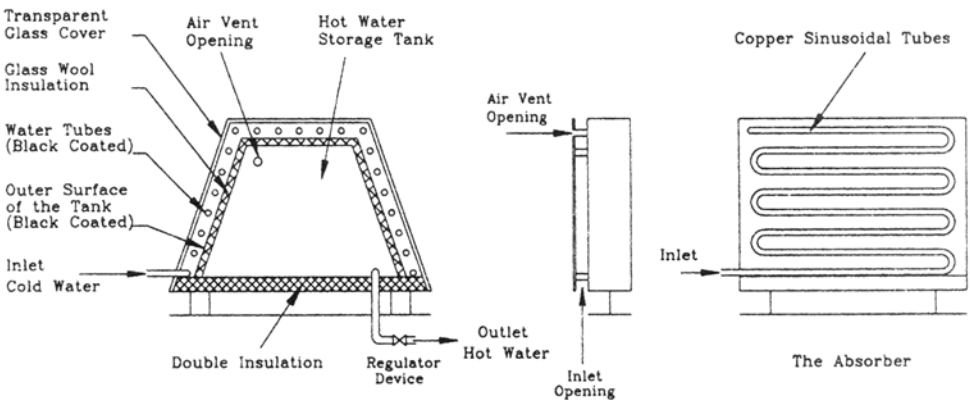

Figure 2. Schematic diagram of the proposed solar water heater.

(iv) increase in the number of the surface area which collect the maximum amount of solar radiation that lead to an increase in the performance of the solar water heater.

The above mentioned factors are employed in solar water heater application which can be applied at will for any solar receiving surfaces.

The proposed design has two advantages: (1) A single unit with one inlet for cold water and one outlet for hot water with simple insulation that can be manufactured to conform to a certain size or even as portable units and (2) The heat losses through the storage tank walls may be minimized since the insulation is very good and the gap between the glass cover and storage tank may be evacuated to minimize the heat losses to the surrounding.

3. Thermal and performance anslysis

3.1 *Thermal Analysis*

The useful heat energy gained by the flat-plate collector, Q_u is the difference between the solar energy absorbed by the collector and the energy lost from it

$$Q_u = F_R A_c [I_T - U_L (T_{f_i} - T_a)], \tag{1}$$

where U_L is the overall heat transferred coefficient, which is the sum of the heat transfer coefficients from the top, bottom and sides,

$$U_L = U_t + U_b + U_s. \tag{2}$$

The major heat loss is from the top, through the cover. It occurs by convection and radiation in the gap between the absorber and the cover, by conduction through the cover and by radiation and convection between the cover and surrounding air. The top heat loss coefficient U_t equation used in this thermal analysis is derived by Mullick and Samdarshi [10],

$$U_t = \left[\frac{(12{\cdot}75(T_{p_m} - T_C)\cos s)^{0.246}}{(T_p + T_C)^{0.46} Z^{0.22}} + \frac{\dfrac{\sigma(T_{p_m}^2 + T_C^2)}{T_p} - T_C}{\left(\dfrac{1}{E_p} + \dfrac{1}{E_C}\right) - 1} \right]^{-1}$$

$$+ \left[\left[h_v + \frac{\sigma E_C (T_C^4 - T_s^4)}{(T_C - T_a)} \right]^{-1} + \frac{t_g}{k_g} \right]^{-1}. \tag{3}$$

The collector heat factor (F_R) represents the ratio of the actual useful heat collection rate divided by the heat rate attainable with the collector absorber surface at the temperature of the fluid entering the collector

$$F_R = \frac{\dot{m} C_p (T_{f_o} - T_{f_i})}{A_C [I_T - U_L (T_{f_i} - T_a)]}. \tag{4}$$

Total solar radiation on tilted surfaces (sides and roof) which are tilted 30° and 15° to the horizontal plane respectively, and the movement of the azimuth angle is supposed to be 15° every hour (i.e. $\omega = 0, \pm 15, \pm 30, \pm 45, \pm 60$, and ± 75).

The total radiation incident on each surface has been calculated using the following equations

$$I_T = I_b \cos\theta + I_d \tag{5}$$

where

$$I_d = I(1 + \cos s)/2 \tag{6}$$

where s is the slope angle of the surface, which is taken as 30° for the sides and 15° for the roof.

$$\cos\theta = \cos\xi \cos s \cos(Az - \gamma) + \sin\xi \sin s, \tag{7}$$

where γ is the azimuth angle of the surface which are 45° for south-east, 0° for south, 45° for south-west and ξ is zinth angle.

The temperature of the collectors can be calculated using the energy balance equation,

$$\dot{m}C_p\frac{\partial T_f}{\partial t} + U_L A_c[(T_f - \Delta T) - T_a] = A_c I_T \tau\alpha. \quad (8)$$

Using the above equations and measured data of direct beam radiation, the incident radiation on the system, temperature of collectors and useful energy were computed.

3.2 *Thermal performance (collector efficiency)*

The thermal efficiency is defined as the ratio between the useful energy collected and the total radiation incident on the surface of the collector. The performance is calculated over day, based on the climate data for the day.

$$\eta_C = \frac{Q_u/A_C}{I_T} = \frac{\dot{m}C_p\Delta T}{I_T A_C}. \quad (9)$$

The data of the characteristics and parameter values of the proposed design are given in table 1.

Table 1. The characteristics, properties and parameters values of the proposed design

Parameter	Value
Length of trapezoidal collector (roof & sides)	(0·8 + 0·6)/2 m
Width of trapezoidal collector	0·6 m
Volume of frustum of pyramid storage tank	(·75 + ·5)/2 × ·5 × ·5 m
Gap space	5 cm
Thickness of used material (galvanized steel sheet)	1·3 mm
Thickness of the glass cover t_g	2 mm
Thermal conductivity of used material	45 W/m°C
Thermal conductivity of glass K_g	0·8 W/m°C
Thermal emittance of glass, E_c	0·84
Thermal transmittance of glass, τ	0·02
Solar absorptance, α	0·95
Solar transmittance, τ_s	0·9
Refractive index of glass relative to air	1·526
Water to tube heat transfer coefficient h_v	205 W/m²°C
Thermal conductivity of the copper tube K_t	211 W/m²°C
Specific heat of copper tube C_{pt}	3·352 kJ/kg°C
Water flow rate G	0·02 kg/s
Outer diameter of the tube d_o	18 mm
Inner diameter of the tube d_i	16 mm
Tube centre-to-centre distance	10 cm
Insulation thickness	4 cm
Insulation thermal conductivity	0·04 W/m°C
Azimuth surfaces angles γ	45°, 0° and −45°
Collectors tilt angles s	30° and 15°
Latitude angle (Cairo) φ	30°

4. Results and discussions

Experiments and computations proved that three angles can be considered as the best angles receiving the highest solar radiation all over the year which are used in this study[11] figures 3 and 4. From this study the tilt angles, 30° and 15° are taken in the present work which are suitable throughout the year.

The variation of hot water for an hourly rate of water consumption of 10, 20, 30, 40 and 60 litres is shown in figure 5. It is found that the highest temperatures are around noon for all cases. Also, that the hot water temperature is highest with lowest consumption.

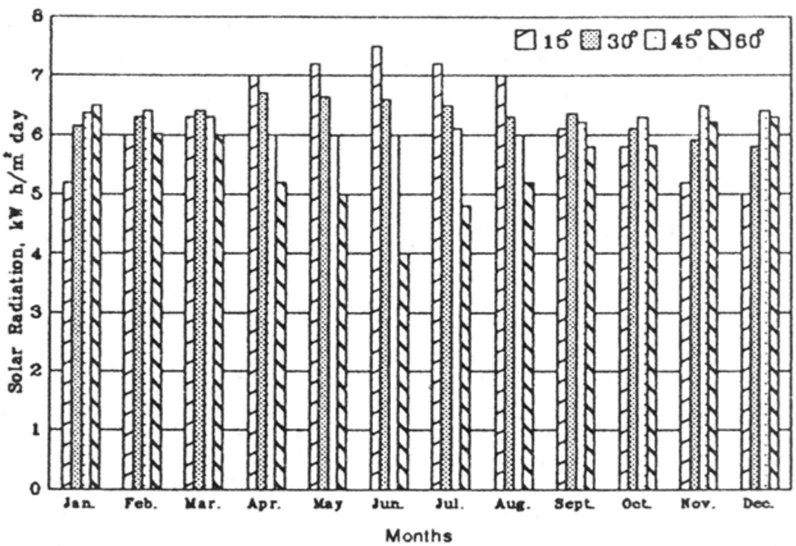

Figure 3. Solar radiation vs months for different tilt angles in cairo, Egypt.

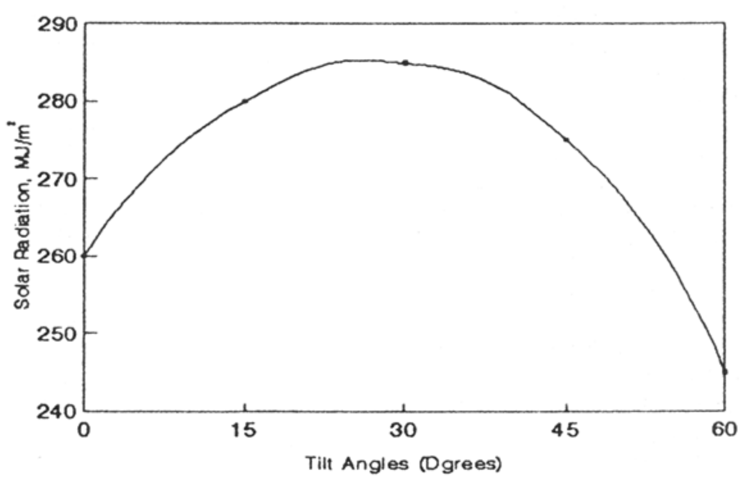

Figure 4. Average solar radiation vs different tilt angles in Cairo, Egypt.

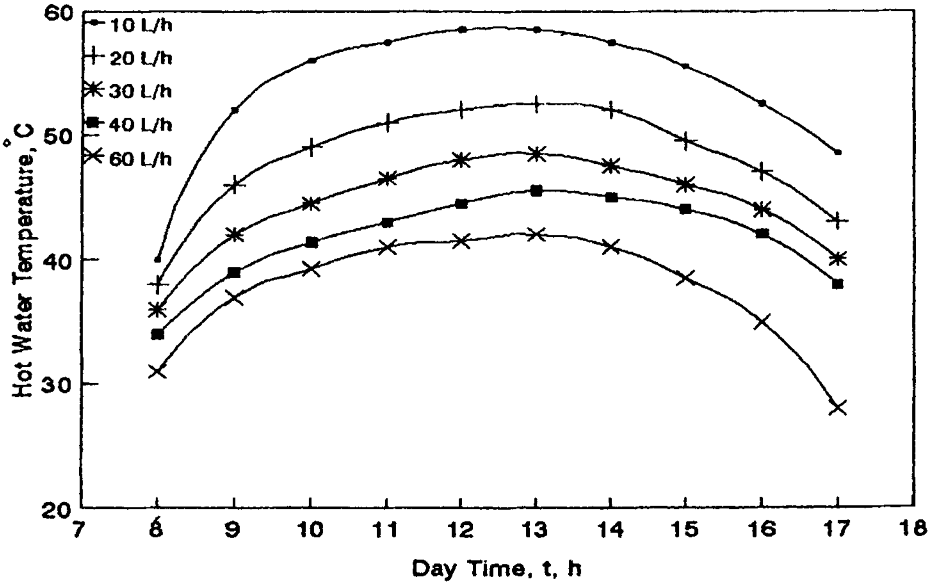

Figure 5. Hot water temperature of compact system during day time (15 June) for various water consumption.

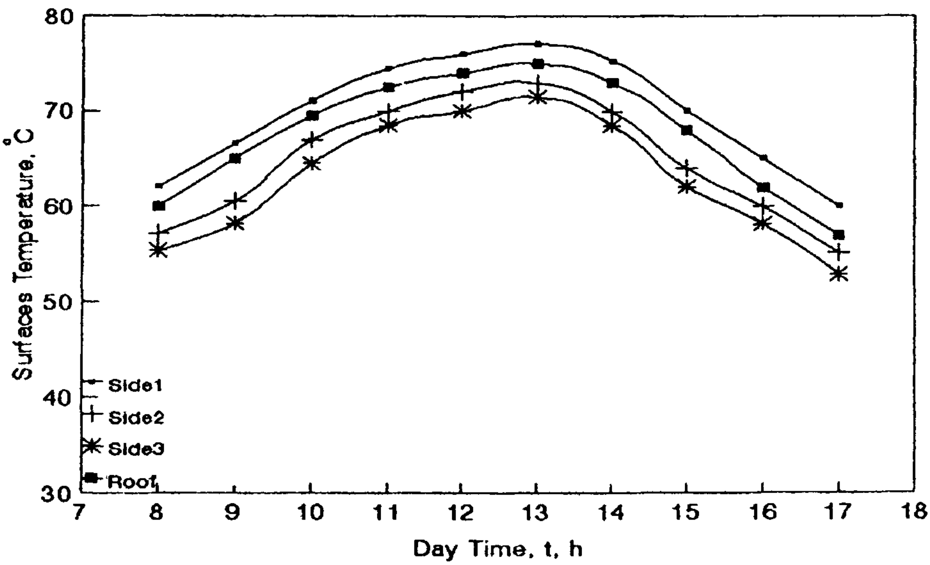

Figure 6. Temperature distribution of the absorber surfaces during day time.

The surface temperature of the absorber plates and ambient temperature have been measured by thermocouples and *m*-voltmeter to give an idea about the circulation of the water flowing from the tubes to the storage tank and viceversa. The average temperature distribution for the surfaces (three sides and roof facing south-east, south and south-west, and the sides tilted 30° while the roof is tilted 15° to the horizontal plane) are given in figure 6. It is found that the temperature distribution of the surfaces facing the south is higher than the other surfaces.

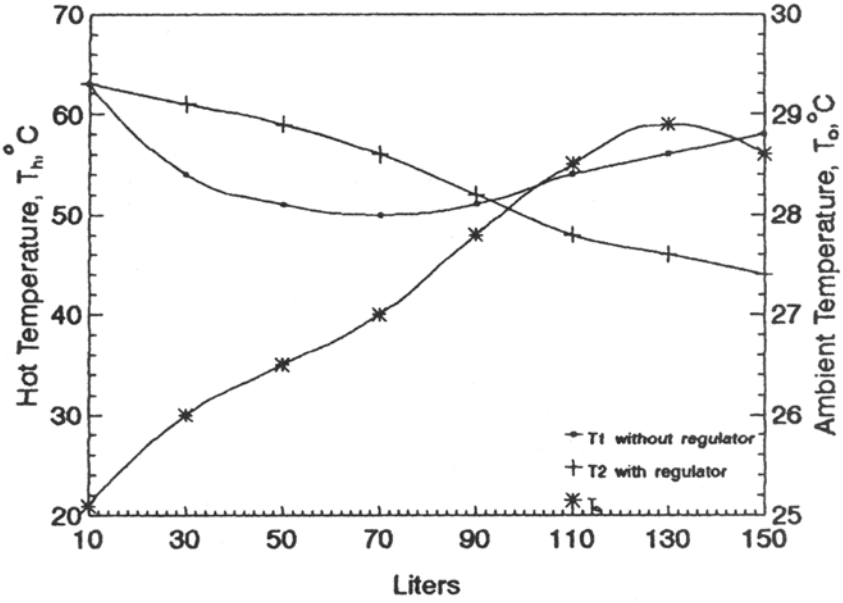

Figure 7. Hot water temperature distribution during consumption with and without regulator.

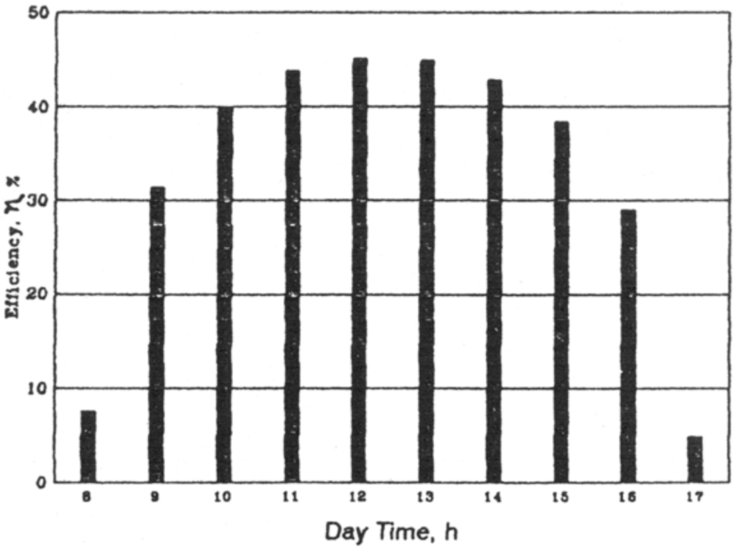

Figure 8. Average of collectors efficiency curve over day (15 June).

The regulator device which is inserted into the piping line of the compact system to prevent the mixing of hot water after sunset has been tested. The variation of hot water temperature during consumption, with and without regulator and the ambient temperature are given in figure 7. It is clear that the regulator device is not practical, since during consumption, the temperature of the hot water varies from hot to cold water and to hot again, respectively and thus it is found that the ordinary tap valve is more suitable.

Table 2. The Numerical values of the performance of the collectors cover over a day 15th June

Day time	08:00	09:00	10:00	11:00	12:00	13:00	14:00	15:00	16:00	17:00
ω	60	45	30	15	0	−15	−30	−45	−60	−75
Z, degree	3·44	40·31	27·45	14·97	6·71	14·79	27·54	40·31	53·44	66·17
Az, degree	98·13	91·61	83·1	66·91	0	−66·91	−83·1	−91·61	−98·13	−104·2
$\cos\theta$ for $\gamma = 0$	0·33	0·31	0·32	0·46	0·92	0·46	0·31	0·30	0·33	0·37
$\cos\theta$ for $\gamma = 45$	0·71	0·78	0·84	0·91	0·67	−0·18	−0·24	−0·16	−0·01	0·16
$\cos\theta$ for $\gamma = -45$	0·81	0·80	0·71	0·94	−0·55	−0·65	−0·37	−0·13	−0·09	0·28
T_a °C	25·2	27	27·5	27·8	28·1	28·3	28·5	29·7	29·9	29·9
T_{pm} °C	61·1	66·6	71·1	74·5	76·1	75·9	73·6	69·9	65·5	60·7
T_{to} °C	60·6	63·3	65·4	67·1	67·7	66·6	64·8	62·7	60·4	58·6
I_b(W/m^2)	213	390	547	665	725	215	615	476	337	186
I_d(W/m^2)	149	192	210	230	230	233	239	221	185	141
I_T(W/m^2)	319·2	535·8	712·4	852·7	914·7	908·2	814·8	658·2	482·8	290·9
I_L, W/m^2°C	3·55	3·62	3·66	3·72	3·72	3·72	3·70	3·65	3·60	3·55
Q_u(W)	37·1	252·5	427·3	560·1	619·5	613·5	524·6	378·2	209·9	20·8
η_c%	7·7	31·4	40·0	43·8	45·2	45·0	42·9	38·3	29·0	4·8

Average efficiency over the day for the proposed type = 37·4%

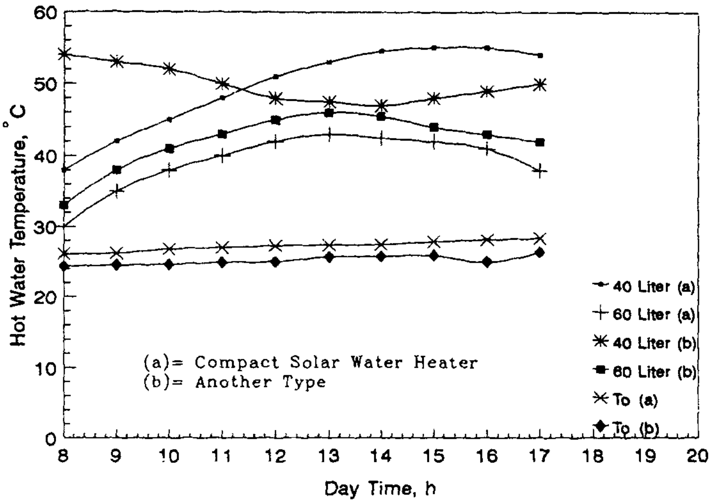

Figure 9. Comparison between consumed amount of hot water of 40 L and 60 L for compact and another type with elevated tank.

It is interesting to study the performance of the collectors over a whole day using data measurements over a day. For the sake of simplicity, the water flow rate, water inlet temperature, and wind speed are all assumed to be constant.

The values of the efficiency of the collectors over 10 h of a day (15 June) is shown in figure 8. It is found that the efficiency increases from 8:00 to 13:00 h touches a peak around noon and then decreases after 13:00 h. This variation indicates the strong dependence on the radiation incident on the collectors over a day. From the results, the average efficiency over the whole period (10 h) during which the useful energy is collected, can be approximately calculated, and it works out to be 37·4%. The numerical values of the performance of the collectors over day (15 June) are given in table 2.

A comparison between compact system solar water heater and other types with elevated storage tanks has been done. The temperature of quantity of consumed water versus day time for both types is given in figure 9. Also, this figure shows the ambient temperature for the same day. It is found that the compact system is efficient after 11:30 a.m. and that the hot water temperature is highest with lowest consumption.

5. Conclusions

The frustum of pyramid solar water heater is proposed towards the development of the solar water heater.

(1). The inclined surfaces of the frustum of pyramid-shaped hot water storage tank may be advantageous in that the flowing hot water slides towards the bottom of the tank and can be used.
(2). The solar radiation crosses the four surfaces (roof + 3 sides) of the frustum of pyramid-shape to heat the cold water supply rapidly.
(3). The compact solar water heater is considered the best efficient design for sunny days to provide a quantity of hot water up to 150 litres for domestic purposes.

(4). The proposed design gives a good performance where by the accumulated energy is always positive all through the year, because winter in Egypt is not too cold.
(5). The average hot water temperature yielded ranges between 40–60°C, depending on the weather and elimatic conditions and the solar intensity.
(6). The compact design of solar water heater offers the distinct advantage of saving area in comparison with the same type having an elevated tank.
(7). The regulator control of the hot water consumption after sunset must be eliminated.

Nomenclature

A_C	collector area, m^2
Az	azimuth angle, degrees
C_p	specific heat, J/kg°C
E	thermal emittance
F_R	collector heat removal factor
h_v	convective heat transfer coefficient, W/m^2°C
I	solar insolation incident on the collector, W/m^2
I_b	direct solar beam radiation, W/m^2
I_d	diffuse radiation on the tilt surface, W/m^2
I_T	total solar radiation on the surfaces, W/m^2
K	thermal conductivity, W/m°C
$\dot{m}$	mass flow rate, kg/s
Q_u	useful energy gained by the collector, W/m^2
Q_1	heat losses by convection, radiation and conduction, W/m^2
s	the slope angle, degrees
t	time, s
t_g	thickness, m
T	Temperature, °C
T_a	ambient temperature, °C
T_f	storage water temperature, °C
T_{pm}	plate mean temperature, °C
ΔT	temperature difference between collector plates and storage water, °C
U_L	overall loss coefficient, W/m^2°C
U_t	top loss coefficient, W/m^2°C
Z	thickness of the air gap, m

Greek letters

α	solar absorbatance
τ	solar transmittance
γ	azimuth angle of surface, degrees
ω	hour angle, degrees
θ	incident angle, degrees
ρ	fluid density, kg/m^3
η_C	collector efficiency
σ	Stefan Boltzman constant $= 5{\cdot}669 \times 10^{-8}$, W/m^2°C
ξ	zinth angle, degrees

Subscripts

a	ambient
b	beam
C	collector-cover plate
d	diffuse
f	fluid
g	ground
i	inlet
o	outlet
p	absorber plate
pm	plate mean
t	top
T	total
s	side

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