STUDY OF SOLAR WATER HEATING SYSTEM WITH NATURAL CIRCULATION IN BASRAH

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Abstract

Theoretical analysis for solar water heating system in Basrah city is performed. The analysis based on the thermosyphon principle in water circulation. The system consists of a tilt flat solar collector connected with isolated water tank by parallel tubes. All calculations are carried out according to Basrah climate conditions in 21 January. The results show that the performance of the solar water heater depends on many parameters such as tilt angle and orientation of the collector, wind velocity, area of the collector, latitude, and solar time. In Basrah where the maximum solar altitude angle in January is about 40, the optimum tilt angle of the collector is found to be closed to 50 degree. The storage water temperature is found to lie between 65 and 95 ^{o}C for the parameters ranges used in the investigation. This temperature range is sufficient for domestic uses in Basrah city.

Keywords: solar water heater, natural circulation system, thermosyphon water heating

دراسة منظومة سخان ماء شمسي يعمل بالتدوير الطبيعي في مدينة البصره

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الخلاصة

تم أجراء دراسة نظريه لمنظومة تسخين المياه باستخدام الطاقة الشمسية في مدينة البصرة. اعتمدت التحليلات النظرية في هذه الدراسة على مبدأ السيفون الحراري كوسيلة لتدوير المياه في المنظومة. تتكون هذه المنظومة من مجمع شمسي مستوي مائل بزاوية مع الأفق يتصل بخزان ماء معزول حراريا عن طريق مجموعة من االانابيب المتوازية. أجريت جميع الحسابات بالاستناد إلى الظروف المناخية السائدة في مدينة البصرة في يوم ٢١ كانون الثاني. أظهرت النتائج إن أداء منظومة السخان الشمسي تعتمد على موقع المجمع الشمسي من الشمس وزاوية ميله عن الأفق ومساحته بألاضافه إلى خط العرض والوقت. في مدينة البصرة حيث تبلغ أقصى زاوية ارتفاع الشمس في كانون الثاني حوالي ٤٠ درجه تكون زاوية ميل المجمع الشمسي المثلى عن الأفق حوالي ٥٠ درجة.وجد أن درجة حرارة الماء في الخزان تقع بين ٦٥و٩٥ درجة مئوية وهي كافيه للاستخدام المنزلي في مدينة البصرة.

Nomenclature

A Collector area , m^2
a Apparent solar irradiation, (W/m^2)
b Atmospheric extinction coefficient, (-)
c_p Specific heat of water, (J/kg ^oC)
D Solar year day number with 1st January
d_c Diameter of collector tube, (m)
g Acceleration due to gravity ,(m/s^2)
H Height of tank, (m)
h Outside heat transfer coefficient, (W/m^2 ^oC)
I Solar intensity, (W/m^2)
L Latitude angle, (deg.)
L_c Length of the collector, (m)
f Pressure drop coefficient ,(-)
M Mass of the storage water, (kg)
$\dot{m}$ Water mass flow rate, (kg/s)
N Number of tubes in the collector, (–)
Re Reynolds number,($\frac{u\,d_c}{\nu}$)
u Water velocity ,(m/s)
T Temperature, (°C)
t Time ,(hr)
v Volume of the storage water,(litter)
w Wind speed, (m/s)

Greek symbols

α Absorbitivity , (-)
β Solar altitude angle ,(deg.)
δ Solar declination angle, (deg.)
θ Surface incident angle ,(deg.)
ψ Solar azimuth angle, (deg.)
γ Surface-Solar azimuth angle,(deg.)
φ Surface azimuth angle,(deg.)
τ Hour angle, (deg.)
ρ Water density ,(kg/m^3)
ϕ Collector plane's inclination to the horizontal, (deg.)
β' Coefficient of expansion of water,(k^{-1})
υ Mean kinematics viscosity of water ,(m^2/s)
ΔP Pressure drops , (N/m^2)

Subscripts

B Buoyancy
c Collector
f Friction pressure drop
m Mean temperature
s Storage tank
o or i Outlet and inlet of the collector, respectively
x Function of x direction
∞ Ambient

Introduction

Hot water domestic uses are one of most common applications of solar energy. The solar water heating system consists of a solar collector and storage tank. The solar collector absorbs the solar energy and transmits to the circulating water in a form of heat. Two ways are used to circulate the water in the system, the first is by pump and the other is by natural circulation due to the action of buoyancy force.

The water heating solar system with natural circulation is the most interesting because of it is simple and most widespread technological device used for solar energy applications. Many studies have been conducted on the solar water heating system.Venkatesh[1]1994 presented experimental and theoretical study for domestic solar water heater with collector area of $1m^2$ and storage tank of $0.16\ m^3$.The maximum solar intensity is taken as $1000\ W/m^2$ and the overall heat loss coefficient is $5.5\ W/m^2\ {}^oC$. He found that the predicted maximum temperature of the storage water is $59.5\ {}^oC$ while the measured is 61^oC.

Haung[2] 1980 has developed a more general theory for parallel-plate absorber water heating systems with natural circulation of water between the plate and tank by representing solar radiation as a sine function of time. Zerrouki et al.[3] 2002 presented an analysis of natural circulation of compact thermosyphon solar domestic heat water system. They assumed that the temperature distribution in the collector is linear. The temperature rise of the water and mass flow rate are measured and calculated.

Koffi et al.[4] 2008 presented a theoretical and experimental analysis of the thermal performance of a solar water heater prototype with an internal exchanger using a thermosyphon system. Their results focus on the levels of the heat fluxes, temperature recorded, mass flow rate and efficiency of the collector. The results indicated that the heat fluxes peak reach 989 w/m^2, collector outlet temperature levels of more than $85.5\,^oC$ and the collector thermal effectiveness 58%.

The present work is focused on a solar water heating system with natural thermosyphon circulation of water. The system analysis is presented for climate condition of Basrah city in the south of Iraq. The objective is to analysis the effect of geometry of the collector and solar radiation during the day as well as the collector tilt on the solar water heating system performance located in Basrah city.

Theoretical Analysis

Detailed information about solar radiation availability at any location is essential for the design and economic evaluation of a solar energy system. It is known that the direct solar radiation on a surface depends on the sun's position in the sky and orientation of the surface (see Figure1).

The sun's position is a function of the latitude (L), the solar declination (δ), and the time (t). From the fundamentals of solar geometry, these parameters are given by [5].

$$\delta = 23.5\sin[(D-80)\frac{360}{365}] \tag{1}$$

$$\tau = 15(t-12) \tag{2}$$

$$\sin\beta = \sin L\ \sin\delta + \cos L\ \cos\delta\ \cos\tau \tag{3}$$

The incident angle θ of solar beams on a surface tiled with the horizontal by angle ϕ is given by [6]:

$$\cos\theta = \cos\beta\ \cos\gamma\ \sin\phi + \sin\beta\ \cos\phi \tag{4}$$

The solar azimuth angle is given by[6]:

$$\sin\psi = \frac{\cos\delta\ \sin\tau}{\cos\beta} \tag{5}$$

When the collector facing south, the surface azimuth angle φ is equal zero, so that $\gamma = \psi$ and then:
The solar intensity on a surface is given by [5]:

$$I = a\,e^{-b/\sin\beta}\cos\theta \tag{6}$$

a and b are monthly dependent parameters tabulated in [5]

1.The solar collector

The water mass flow rate through the collector can be evaluated from the heat and mass transfer balance between the buoyancy and pressure in the thermosyphon loop caused by the difference in densities of the hot and cold water and the pressure losses in the collector pipes according to the following equation(see Figure2):

$$\Delta P_B = \Delta P_f \tag{7}$$

Where ΔP_B indicates the driving force for the natural circulation, while ΔP_f refers to the total pressure drops along the loop.

ΔP_B consists of two parts, one representing the pressure drop across the collector ΔP_c and the other between the top and bottom of the storage tank ΔP_s:

$$\Delta P_B = \Delta P_c + \Delta P_s \tag{8}$$

The pressure due to the buoyancy force ΔP_B can be evaluated by the following equation [3]:

$$\Delta P_B = g\beta'\rho_o \sin\phi \int_0^{L_c} (T_{(x)} - T_i)dx + g\beta'\rho_o (T_o - T_i)H \quad (9)$$

The temperature distribution in the collector tubes can be described by a linear equation of the following form:

$$T_{(x)} - T_i = \frac{T_o - T_i}{L_c} x \quad (10)$$

Integrating equation (9) yields:

$$\Delta P_B = g\beta'\rho_o (T_o - T_i)\left[\frac{L_c \sin\phi}{2} + H\right] \quad (11)$$

At the equilibrium, the buoyancy force is equal to the friction resistance in the flow path, then:

$$\Delta P_f = \Delta P_B = g\beta'\rho_o (T_o - T_i)\left[\frac{L_c \sin\phi}{2} + H\right] \quad (12)$$

The friction pressure drop in the collector tubes is expressed by:

$$\Delta P_f = \frac{1}{2}\rho f \frac{u^2 L_c}{2 d_c} \quad (13)$$

For a laminar flow, f is given by:

$$f = \frac{64}{Re} = \frac{64\nu}{d_c u} \quad (14)$$

For set of parallel tubes (N) of the collector, the mass flow rate is given as:

$$\dot{m} = \frac{\pi}{4} N \rho u d_c^{\,2} \quad (15)$$

Or

$$u = \frac{4\dot{m}}{N\rho\pi d_c^{\,2}} \quad (16)$$

Equations 12 to 16 give:

$$128\frac{\nu L_c \dot{m}}{\pi N d_c^{\,4}} = \rho_o g\beta'(T_o - T_i)\left[\frac{L_c \sin\phi}{2} + H\right] \quad (17)$$

The temperature difference $(T_o - T_i)$ can be evaluated from the heat balance of the collector as follows:

$$T_o - T_i = \frac{I\alpha A_c - h A_c (T_m - T_\infty)}{\dot{m} c_p} \quad (18)$$

Where

$$T_m = \frac{T_o + T_i}{2} \tag{19}$$

The heat transfer coefficient as a function of wind speed is given by [7]:

$$h = 2.8 + 3u_{wind} \tag{20}$$

2. The Storage Tank

By considering the storage tank insulated, the energy balance can be given as:

$$M c_p \frac{dT_s}{dt} = \dot{m} c_p (T_o - T_i) \tag{21}$$

The mass flow rate ($\dot{m}$) and the temperature difference $(T_o - T_i)$ vary with time as the solar incidence varies during the day.

3. Solar Intensity in Basrah City

As mentioned previously, the solar intensity can be calculated using equations 1 to 6. It is noted that the solar incidence on a surface depends on six variables: the solar declination (δ), the latitude (L), the time (t), the surface-solar azimuth angle (γ), the surface azimuth angle (φ), and the surface angle (ϕ). Equation (6) represents the final equation where the solar incidence for any location can be calculated.

Basrah city lies on latitude (30.4 N), for a surface facing the south in 21 January, the data evaluated form equation (6) is fitted to the following formula:

$$I = (103\phi^3 - 741\phi^2 + 1017\phi + 628)\sin\left(\frac{\pi t}{day}\right) \tag{22}$$

Where

day: is the time difference (in hours) between the sunrise and sunset.

t : is the time (in hours) from the sunrise.

The theoretical study is performed for the Basrah climate conditions in 21 January. To obtain the desired results, the geometrical parameters using in this study can be summarized as:

Collector area $A = 3m^2$

Collector tube diameter d_c =10 cm

Number of collector tubes N=20

Volume of water storage 120 lit.

Absorbitivity $\alpha = 0.9$

The ambient temperature in Basrah (21 January) for the last years(2004-2007) [8] is 7-17 ^{o}C and the wind velocity is 2-7 m/s. the water thermophysical properties used in the calculations is given by the following relations[9]:

$$\rho = 1001 - 0.08832T - 0.003417T^2 \quad (23a)$$

$$c_p = 4226 - 3.244T + 0.0575T^2 - 0.0002656T^3 \quad (23b)$$

$$\beta' = (0.3 + 0.116T - 0.0004T^2)10^{-4} \quad (23c)$$

$$\upsilon = (\frac{1}{0.5155 + 0.0192T} - 0.12)10^{-6} \quad (23d)$$

Results and Discussion

The solar radiation incident on the titled solar collector considered in this study depends on altitude angle (β) and the incident angle (θ) as shown in equation (6). These two angles can be easily evaluated from equations (3) and (4) respectively. **Figure(3)** shows the altitude angle(β) vs. time in 21 January and latitude (30.4). The altitude angle (β) increases from zero at sunrise to reach its peak value at solar noon and decreases after that to reach zero at sunset. In 21 Jan. the declination angle is about -20 deg. and the maximum value of altitude angle (β) at latitude 30.4 is about 40 deg.

In **Figure(4)** the solar radiation incident on the tilted collector surface increases with increasing the tilted angle(ϕ) to reach a maximum value at about $\phi = 50$ deg. and it decreases after that. This is because the maximum solar radiation is obtained when the collector facing a normal direct radiation. At solar noon the solar azimuth angle $\gamma = 0$ and the equation (4) reduces to $\theta = 90 - \beta - \phi$. For a surface facing the south $\beta = 40$ deg. and the incident angle becomes $\theta = 50 - \phi$. It is clear that $\theta = 0$ when the tilt angle $\phi = 50$ which means a normal (maximum) solar radiation incident on the tilted collector surface.

The differential equation (21) is solved numerically by Euler method using equations (17 and 18) to calculate the hourly storage water temperature (T_s). The results are shown on **Figures (5-10). Figure (5)** shows the effect of the tilt angle of the collector on the storage water temperature. It is noted that water temperature (T_s) increases with the tilt angle for the range considered since solar radiation increases with the tilt angle for this range as it explained previously.

As expected an increase of the collector area increases the heat absorbed by the water as it clear in **Figure (6)**. It is also noted the water temperature fall sharply for the larger area due to the increase of heat loss by the wind. This situation shown in **Figure (7)** where the wind has a significant effect on the heat transferred to the water. When the wind velocity increases, the heat transfer coefficient increases and the heat loss from the collector increases which in turn a decrease in the water temperature. For a specified collector dimensions a quantity of heat absorbed by the collector can be evaluated. When the volume of storage water is large, the water temperature decreases and the water requires more time to heat up as it shown in **Figure(8).**

In **Figure (9),** a sine profile shown for the solar intensity with a maximum value in mid-day . The solar intensity increases with a tilt angle of the collector in a range $\phi = 15 - 60 \text{ degree}$ since the radiation approaches a vertical to the collector surface when the tilt angle is close to 50 degree as it shown in **Figure(4).**

Figure (10) shows the water output temperature at the collector exit. It is noted that the water temperature T_o increases with the tilt angle and reach a peak value when the tilt angle reaches 50 degree. After that it decreases since the radiation incidence is normal at about $\phi = 50 \text{ degree}$ and a tilt otherwise.

Figure (11) shows a comparison between the present model and the experimental data presented by Venkatesh[1]. The predicted storage water temperature is higher than that measured by Venkatesh because the heat loss from the storage tank is neglected in the present work while it considered by Venkatesh work.

Conclusions

1- The optimum tilt angle of the collector facing the south in Basrah during January is about 50deg. to the horizontal.
2- A solar water heating system with a collector area of $2m^2$ provides 120 litter/day of water at about 65 ^oC which is sufficient for domestic uses.
3- The peak value of storage water temperature is always shifted from mid-day to afternoon due to the effect of heat capacity of water.
4- The performance of the solar water heater is strongly depends on parameters like, the collector location, collector tilt, wind velocity, and the solar time.

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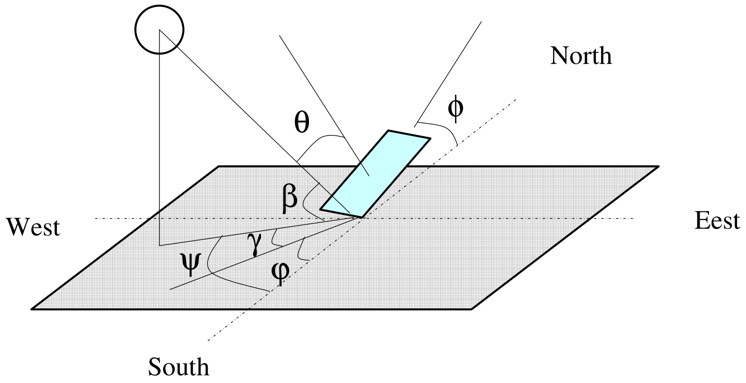
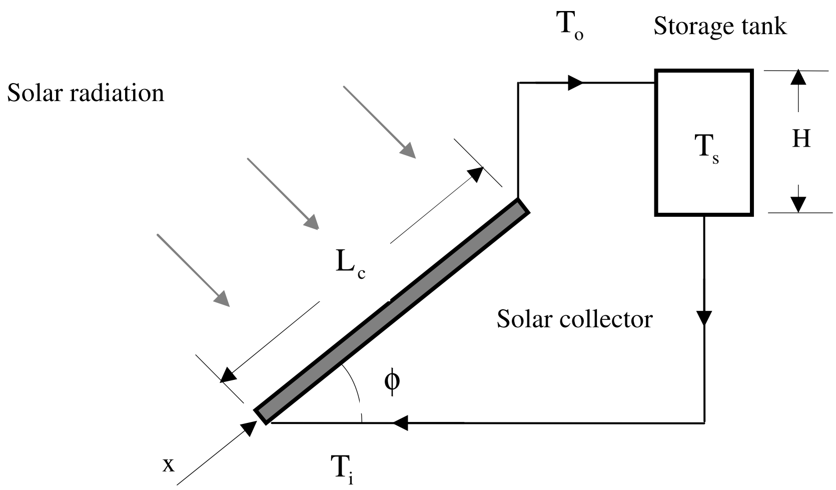


Figure (1) solar angles for a titled surface.



Figure(2) Natural circulation solar water heater system.

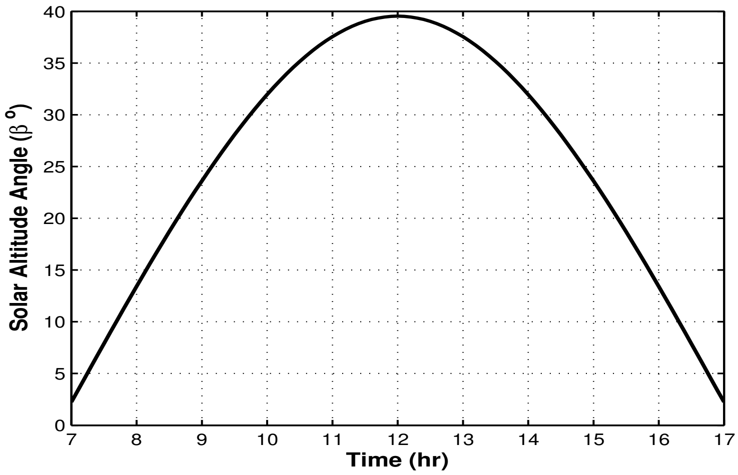


Figure (3) solar altitude angle in Basrah(21 Jan.) as a function of time.

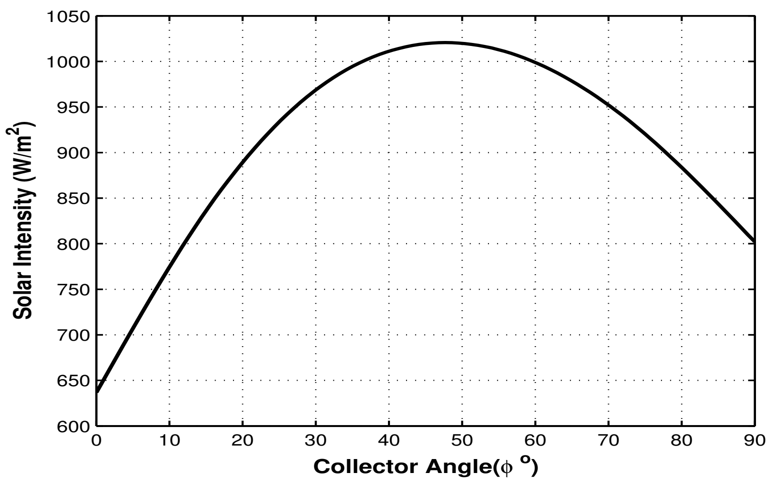


Figure (4) variation of solar intensity with collector angle ϕ.

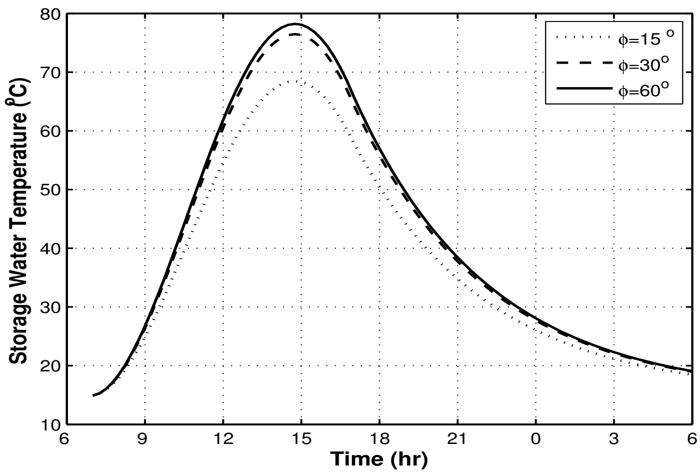


Figure (5) effect of collector angle on storage water temperature.

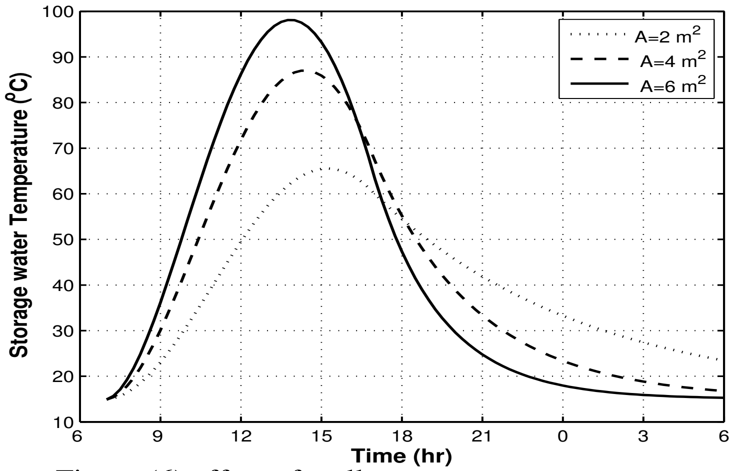


Figure (6) effect of collector area on storage water temperature.

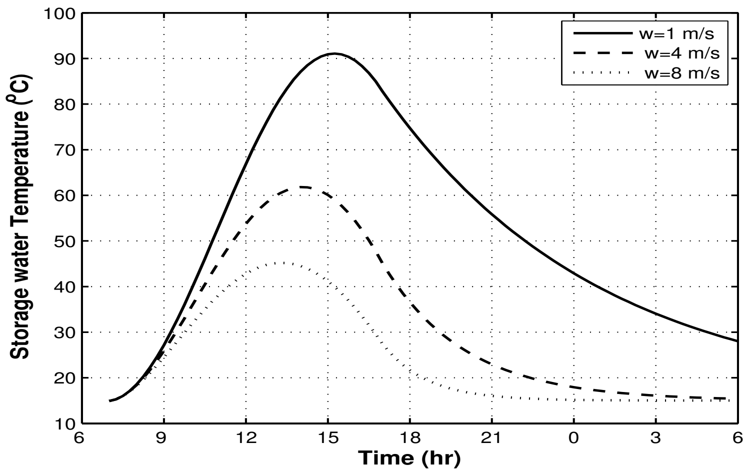


Figure (7) effect of wind velocity on storage water temperature.

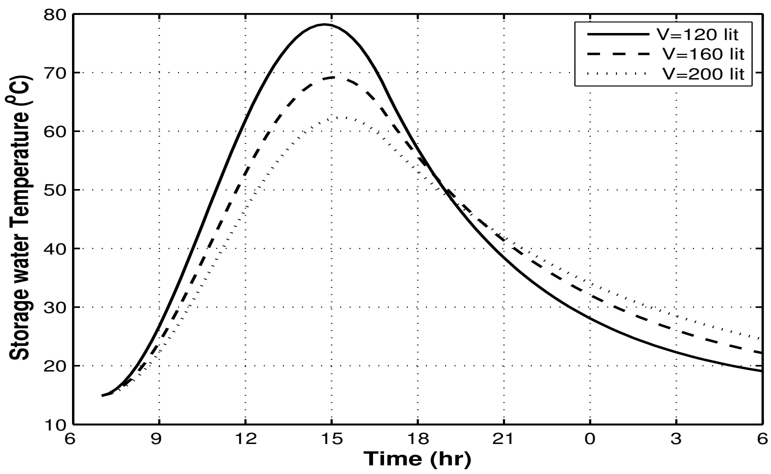


Figure (8) effect of storage water volume on the water temperature.

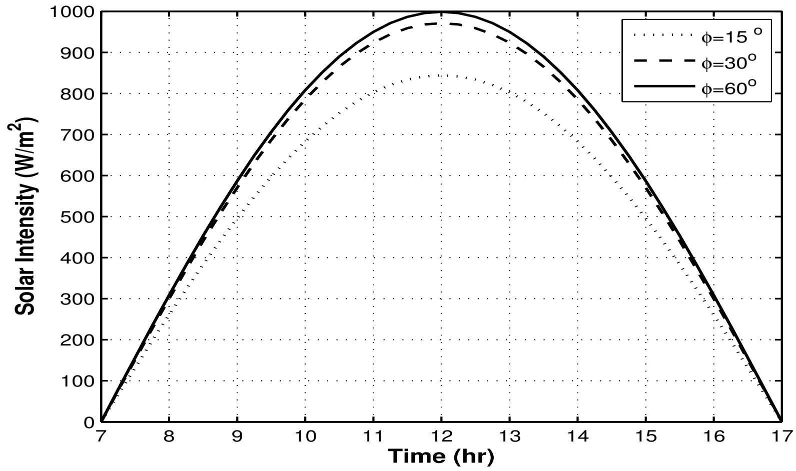
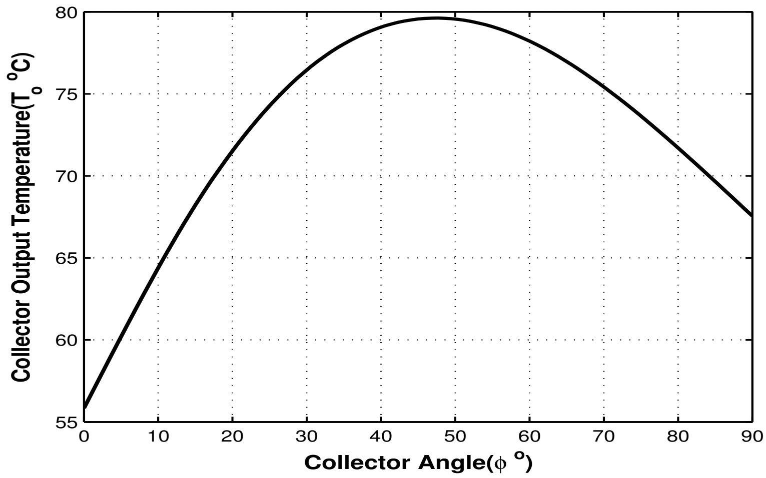
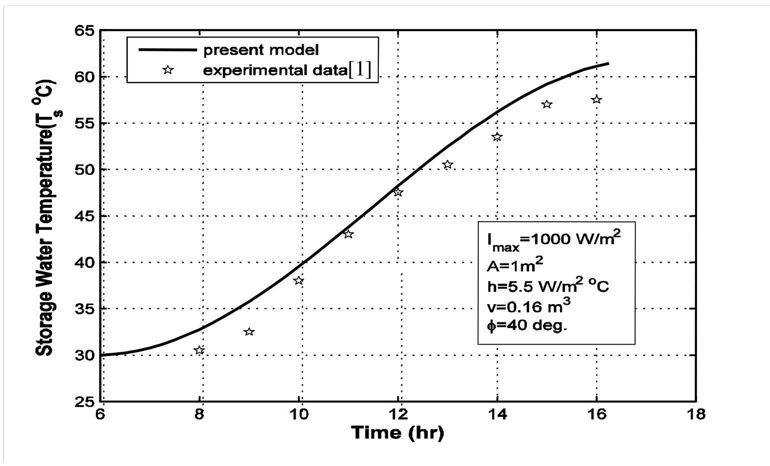


Figure (9) effect of collector angle on solar intensity.



Figure(10) output water temperature as a function of collector angle ϕ.



Figure(11) Comparison between the present model and experimental data presented by Venkatesh[1] .