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Thermal Performance Analysis of a Fully Mixed Solar Storage Tank in a ZEB Hot Water System

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Abstract The intermittency is inherently affects the solar energy as the main hot water supplier in renewable systems. Therefore, the storage of the hot water is a vital part of a reliable energy supply system for buildings. Using a proper storage system makes it possible to fill the shortfall or emergency periods. This paper studies the daily thermal performance of a horizontal solar storage tank. It is assumed that the hot water load is similar to the Rand profile and the auxiliary heater is a biomass-fired boiler. The Rand profile assumes a daily hot water of consumption of 120 liters for a family of four. Furthermore, the tank is considered to be fully mixed because its height is relatively low. It means that the temperature in the solar zone of the tank is uniform. This assumption simplifies the analysis because the storage and the load temperature would be the same. The profiles for the storage water temperature, solar fraction and the useful energy gain was obtained and the effects of principal parameters are studied.

Keywords: *solar energy, storage tank, Domestic Hot Water (DHW), Building Energy Simulation*

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1. Introduction

Zero Energy Building (ZEB) is a concept based on minimized energy demand and maximized harvest of local renewable energy resources. In these buildings, the electricity or heat from renewable energy resources can supply the same highly reduced energy demands [1,2].

Zero energy buildings are usually designed to utilize passive solar heat gain. For the purpose of space heating, the system is integrated with a thermal mass storage to fix diurnal indoor temperature variations. Along with that, the system should be able to provide hot water especially in domestic applications. The water heating systems are always inseparable parts of the residential buildings.

Approximately 18% of energy use in residential buildings and 4% in commercial buildings is for water heating. The hot water energy consumption is between about 220 *kWh* and1750 *kWh* per person and year for low energy demand and high energy demand patterns, respectively. The pattern consumption for the middle requirement range between 30 liters and 60 liters per person and day, with the warm water temperature of 45°C. The consumption is 440 *kWh* to 880 *kWh* per personequal to 1760 *kWh* to 3520 *kWh* for an average four-person household [3].

It is obvious that the *solar water heating systems* (SWH) can heat potable water only throughout the day and only when the sun is shining and the solar radiation is hitting the solar collector. Since the supply and the demand of thermal energy cannot usually be kept in balance, energy storage will play an important role for sustainable utilization. So it is essential for a solar water heating system to be accompanied with a thermal storage tank.

2. Solar Water Heating Components

As it can be seen from the schematics of a domestic solar water heating system depicted in Figure 1, a SWH is comprised of three main parts: *solar collector array*, *storage tank* and the *energy transfer system*.

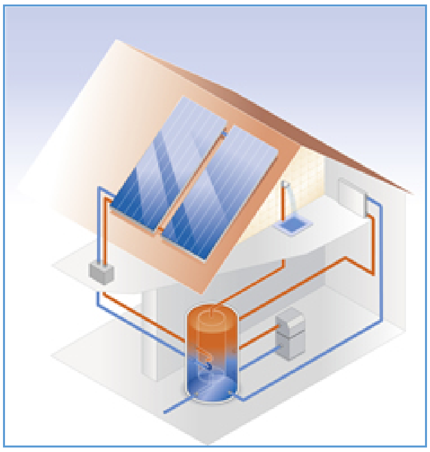

Figure 1. Schematics of solar water heating system components

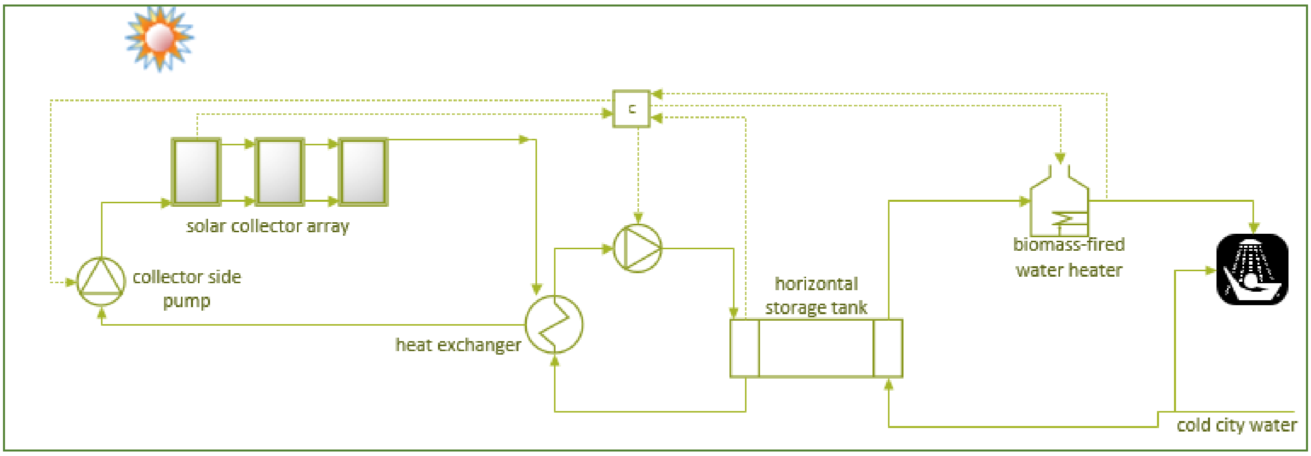

Figure 2. Schematics of a ZEB water heater system

2.1. Solar Collector Array

Solar collector arrays are normally mounted on the roof or placed on the ground. They transfer the absorbed thermal energy from the sun to a heat transfer fluid which can be water or a solution. Collectors can be *flat plate* or *evacuated tube*. Flat plate collectors are typically single glazed but may have an extra second glazing layer to improve their heat gain.
However, flat plate air collectors are mainly used for space heating purposes only. To produce both heat and electricity, flat plate air collectors are usually connected with photovoltaic panels. The more elaborate the glazing system, the higher the temperature difference that can be sustained between the absorber and the external wall. In general, most black paints which are widely used as the absorber plate color, reflect nearly 10% of the solar incident radiation.

2.2. Storage Tank

Storage tank is an insulated hot water tank that stores they gained thermal energy for later, shortfall or emergency uses. In *indirect systems*, the storage water in the tank receives the thermal energy from the heat transfer solution in the collector side loop through a heat exchanger which can be located inside or outside the storage tank or it can be served as its mantle. In *direct systems*, the potable existing is heated and used, directly.

Water storage tank systems designs are typically based on the exploiting of the warm and cold water tendency to stratify, i.e. the cold water is placed in the bottom of the tank while warm water is returned to or drawn from its top. A 9 in to 15 in boundary layer or thermoclineis formed between the warm and cold zones. Special mechanical designed diffusers or any array of nozzles assure the mixing phenomenon since the laminar flow is established within the tank. This laminar flow is necessary to increase stratification since the densities of return warm water and the supply water are 60°F and 40°F to 42°F respectively which are almost identical.

There are two types of solar storage tanks based on the thermal stratification: *fully stratified water tanks* and *fully mixed water tanks*. Comparison between these tanks employed in many solar water heating applications shows that the efficiency of the energy storage and the whole system may be increased up to 6% and 20%, respectively [4]. The penalty associated with horizontal tanks is that the shallow tank depth degrades thermal stratification because of conduction through the walls of the tank and water [5].

2.3. Energy Transfer System

It uses liquid inside pipework which flows from solar energy collector array to the hot water storage tank. A *passive* transfer system does not involve mechanical devices such as pump or fan except for the energy needed to regulate dampers and/or controllers. *Active* solar uses electrical or mechanical equipment for the conversion of solar radiation into heat.

3. Model Equations

Model presented here is pertained to a system with schematics illustrated in Figure 2. At any hour *j*, the useful energy Q_u^j gained by the collector array with the area A_c can be expressed with equation (1).

$$Q_u^j = A_c F_R' [G_t^j(\tau\alpha) - U_{L,C}(T_i^j - T_a^j)] \qquad (1)$$

Where F_R' is the modified collector heat removal factor, $U_{L,C}$ is the overall heat loss coefficient from the collector (W/m^2°C), T_i^j is the collector inlet temperature (°C) at hour *j*, °C), G_t is the irradiation (W/m^2) which its values can be found in Figure 3, T_a^j is the ambient temperature (°C) at hour *j* and its values can be found in Figure 4 and $\tau\alpha$ is the product of the glass transmittance and the absorber absorptivity. It should be noted that the useful energy gain is always a positive. The factor F_R' is the consequence that occurs because the heat exchanger causes the collector side of the system to operate at a higher temperature than a similar system without a heat exchanger. The modified collector heat removal factor takes into account the presence of the heat exchanger and is given by

$$F_R' = F_R\{1 + \frac{A_C F_R U_L}{(mC)_C}[\frac{(mC)_C}{\varepsilon(mC)_{min}} - 1]\}^{-1} \qquad (2)$$

where for the dimensionless capacitance rate $\zeta \neq 1$, we have

$$\varepsilon = \frac{1 - e^{NTU(1-\xi)}}{1 - \xi e^{NTU(1-\xi)}} \quad (3)$$

$$NTU = \frac{UA}{(mC_p)_{min}} \quad (4)$$

and

$$\xi = \frac{(mC_p)_{min}}{(mC_p)_{max}} \quad (5)$$

In the above equations, C and m are the specific heat (*J/kg K*) and mass flow rate, respectively. Specifications for the heat exchanger can be found in Table 1.

For any instant of the time, energy balance for the storage tank can be written as the following.

$$m_t C \frac{dT_t}{dt} = Q_u - Q_i + Q_d \quad (6)$$

Where m_t is the mass of storage tank water content (kg)with specific heat c which are both assumed to be fixed over the period of analysis (1 hour) and T_t is the storage tank water temperature (°C). The term Q_d is the demanded hot water energy per unit of the time (W) and Q_i is the system thermal loss (W). Using the finite difference approximation with a time step of 1 hour, Eq. (2) can be simplified into

$$m_t C(T_t^{j+1} - T_t^j) = Q_u^j - U_{L,t}(T_t^j - T_r) - U_{L,p}(T_t^j - T_a^j) + m_d^j C(T_t^j - T_c) \quad (7)$$

The extracted thermal energy corresponds to drawing of hot water with the mass m_d^j (kg) for the house at the top of the tank and replacing it with the cold make-up water from the mains inlet with temperature T_c (°C) and with the same mass at the below of the tank.

Furthermore, the system thermal loss can be expressed as the thermal loss from the tank $Q_{L,t}$ (Wh) and the thermal loss from the piping system $Q_{L,p}$ (Wh). $U_{L,t}$ and $U_{L,p}$ are the overall heat loss coefficients ($\frac{Wh}{°C}$) from the tank and the piping system, respectively, and T_r (°C) is the room temperature in which the tank is located. Values for different constants in equations (3) can be found in Table 2. Pipe surface temperature T_p^j is not uniform along the pipe length, therefore it is assumed that the heat loss from the piping is at its maximum rate by considering $T_p^j = T_t^j$.

Since the tank is fully mixed, the collector inlet temperature is assumed to be equal to the tank temperature, $T_p^j = T_t^j$. If the system is not able to provide the desired hot water outlet temperature which is $T_{set} = 50°C$, an auxiliary heater will be used to compensate the shortage in thermal energy. The *solar fraction* is defined as

$$f = \frac{Q - Q_d^j}{Q} \quad (8)$$

Where Q is the required hot water energy for the building:

$$Q = Q_d^j + m_d^j C(T_{set} - T_t^j) \quad (9)$$

or

$$f = \frac{T_{set} - T_t^j}{T_{set} - T_c} \quad (10)$$

Using MATLAB to utilize a method developed by Kalogirou [5] or Duffie & Beckman [6] the hourly tank temperature and the solar fraction can be found. To start the algorithm, an initial condition is needed for the temperature in the tank as

$$initial\ condition: T_t^6 = 40°C \quad (11)$$

The hot water daily consumption profile for m_d can be obtained by the Rand profile [7] which is shown in figure (4).

Table 1. Design parameters for heat exchanger

Parameter	Value
fluid	water glycol
c	3840 j/kg °C
m	1.35 kg/s
UA	5650 W/°C

Table 2. Values for design parameters used in the model

Parameter	Value
A_c	10m2
F_R	0.918
τa	0.9
$U_{L,C}$	7.5 W/m^2°C
$U_{L,t}$	3.5 W/°C
$U_{L,p}$	20 W/°C
m_t	500 kg
T_r	22°C
T_c	18°C
c (water)	4180 j/kg °C
m (water)	0.95 kg/s

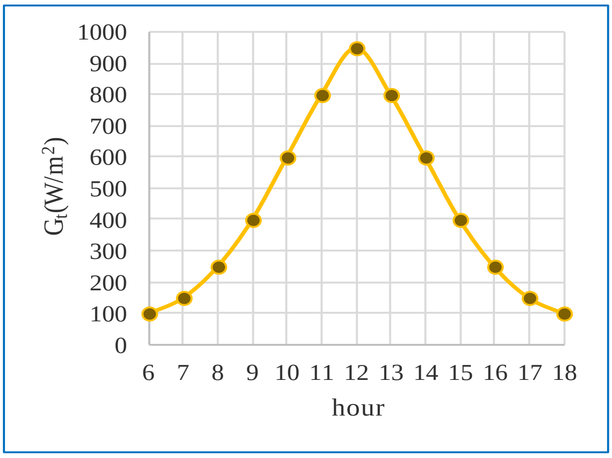

Figure 3. Distribution of Solar radiation in the analysis period

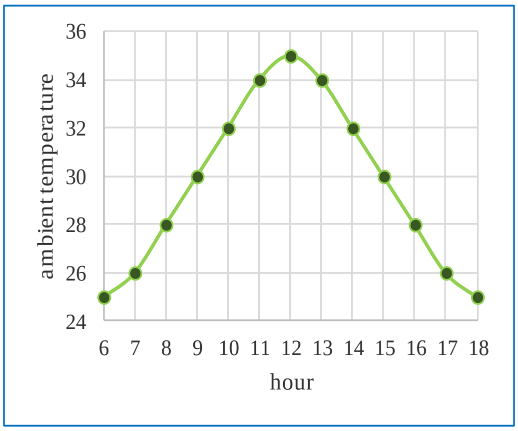

Figure 4. Ambient temperature in the analysis period

4. Results and Discussions

The useful energy gained throughout the day, temperature variation in the tank and the solar fraction are illustrated in Figures 6 to Figures 8. As it can be seen from Figures 7, the maximum energy gain is happened at noon because at this time the radiation is at its maximum level. The ambient temperature is relatively high and as a result, the losses are relatively low. The demand for hot water is descending between hours 10 and 15 so the temperature rises in the tank and reaches its maximum level at 15:00. The solar fraction was below 1 only for 6 hours a day (33% of the total time) and the modeled system is efficient enough to supply hot water for a small building however, its value never falls below 0.6. Note that the analysis is based on the Rand profile. The Rand profile assumes a daily hot water of consumption of 120 liters for a family of four. Another important point is the source which is used for the auxiliary heater in Figure 2. The fuel is biomass and the system is totally renewable and environment friendly.

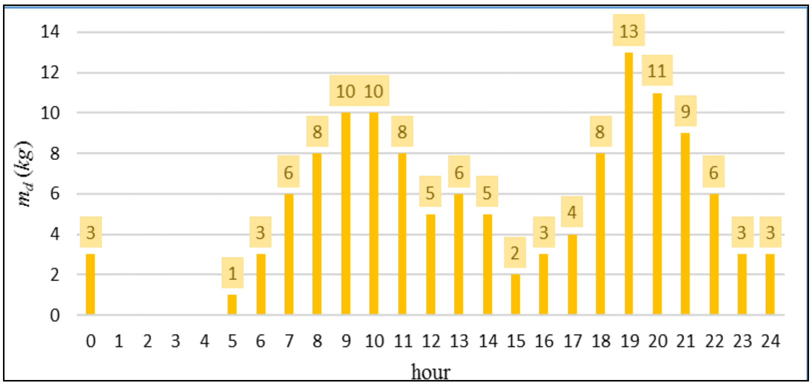

Figure 5. Rand profile for hot water energy consumption

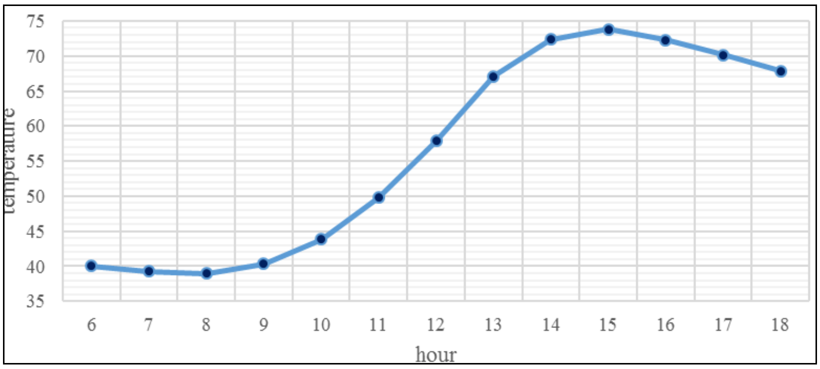

Figure 6. Hourly temperature in storage tank and supply for the load

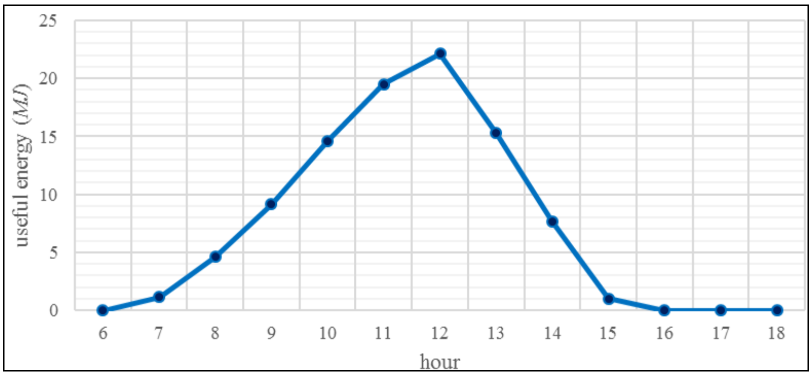

Figure 7. Useful energy gained by the solar heating system

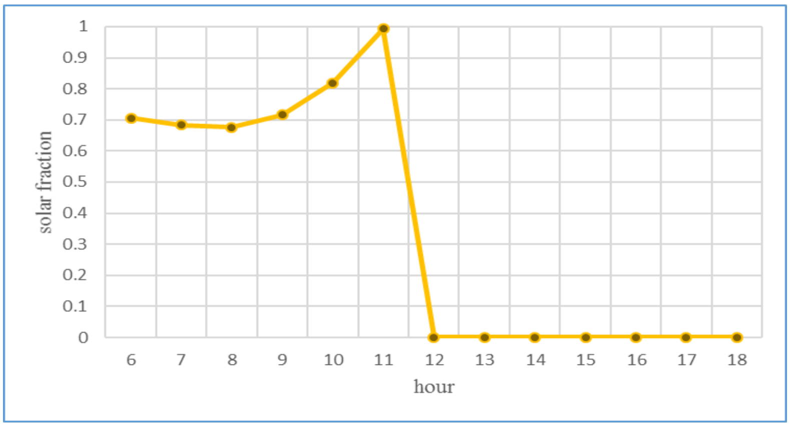

Figure 8. Solar fraction for the water heating systems

5. Conclusions

Zero energy buildings are usually designed to utilize passive solar heat gain. Temperature distribution in a fully mixed tank was modeled to obtain the temperature profile, solar fraction and useful energy gain. The solar fraction was below 1 only for 6 hours a day (33% of the total time) and the modeled system is efficient enough to supply hot water for a small building however, its value never falls below 0.6. The maximum in-tank temperature is happened in the low-demand hours when there is a chance for the tank to increase its temperature while no cold water can enter it. The minimum in-tank temperature happens in the morning while the demand is increasing and no enough radiation hits the collector. It is recommended to study the effects of the volume in the storage tank along with another thermal mass to achieve a complete hot water supply for the building. Also, it is recommended to propose a design for combined space heating and hot water.

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