Performance Analysis of a Hybrid Solar Energy Storage System

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—Technical Note—

PERFORMANCE ANALYSIS OF A HYBRID SOLAR ENERGY STORAGE SYSTEM

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ABSTRACT

In this work, a method for increasing the storage capability of a solar thermal energy system has been discussed. The system includes two tanks with the flexibility in choosing the best storage medium on the basis of the solar collector's outlet temperature. The results show that using such a hybrid storage system, the storable energy can be increased. Comparing the results with those for simple common storage systems, the extent of improvement was calculated.

For verification of the results, a small pilot system was assembled. The test apparatus operated during 2008-2009 cold months and the parameters were recorded. Comparison of the theoretical and experimental results showed a good agreement.

Keywords : Solar, Thermal energy, Storage, Hybrid, Optimization.

1. INTRODUCTION

The intermittent nature of solar energy and the energy requirements of buildings necessitate the storage of thermal energy. Most of the solar energy storage systems use sensible heat storage [1], though using latent heat storage systems have also been considered. Moreover, reversible chemical reactions are the subject of recent studies for thermal energy storage.

Despite the variety of thermal energy storage methods, an optimum economical point is not agreed. The development of remote, renewable-based energy is hindered in part by the lack of affordable energy storage. Requiring power-on-demand from an energy system powered by intermittent or seasonal sources may necessitate energy storage. If multiple energy storage devices with complementary performance characteristics are used together, the resulting 'hybrid energy storage system' can dramatically reduce the cost of energy storage in comparison to single storage systems [2].

Hybrid energy storage systems using more than one medium for complementary performance have been the subject of some studies. The model of a solar pow-

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ered, battery-hydrogen hybrid energy storage system was developed by Vosen and Keller [2]. Parker and Clapper [3] have also developed and patented such an innovative energy storage system. Hammou and Lacroix [4] have considered a hybrid thermal energy storage system (HTESS), using phase change materials, for managing simultaneously the storage of heat from solar and electric energy. Zohoor and Moosavi [5] have discussed a method for finding the optimum performance state to increase the storage capability of a solar hybrid energy storage system. They have also extended the method to a one-year period and compared the results against simple common storage systems [6].

2. DESCRIPTION OF THE SYSTEM

A Hybrid Energy Storage System (HESS) consists of several media for storage. The HESS designed in this research includes a water tank and a PCM tank. It should be mentioned that a mixture of 80% Residue wax and 20% Slack wax was used as the PCM medium. More information about these waxes is described in the section (4).

Solar energy is absorbed through two flat plate thermal collectors each having an area of $2m^2$. The working fluid in solar collectors is a 50:50 mixture of water and ethylene glycol. The working fluid flows in the pipes of the collectors and tanks so that heat is stored in storage tanks. Suitable pipe work and control valves enable the choice of the tank in which the working fluid is supposed to flow depending on the control system switching (Fig. 1). A circulating pump circulates the working fluid in the system with the flow rate of 0.04kg/s during charging or discharging. Other pipelines are also included in the system. During the heat recovery hours, these pipes direct the working fluid toward the end user. The end user is a radiator with eight fins which transfers the heat to a room with the area of $4.2m^2$. The room is a section of an office in the north of Tehran (35°N). North Tehran is 1548m above the sea level. The system stores the energy throughout the day and when required it is used for heating a room or a hot water tank or flow. Heat recovery begins after the decrease of the intensity of the solar radiation.

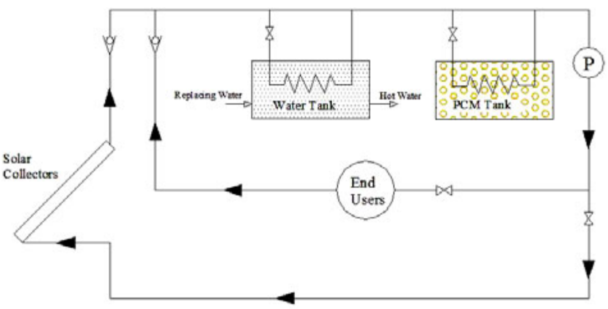

Fig. 1 Schematic of the solar hybrid storage system

To determine the amount of the stored and recoverable heat, the analysis of heat transfer is necessary. In the assumed system of this problem, the amount of the total stored energy equals the sum of the stored energy in water and PCM tanks:

$$E_{in} = Q_{win} + Q_{pin} \tag{1}$$

where, Q_{win} and Q_{pin} are the stored energy in the water and PCM tanks respectively. Similarly, the amount of total output energy equals the sum of recoverable energy of the water and PCM tanks:

$$E_{out} = Q_{wout} + Q_{pout} \tag{2}$$

where, Q_{wout} and Q_{pout} are recoverable energy of water and PCM tanks respectively. For each day, energy storage begins at 8:30am and ends at 16:30. There is almost no useful sun radiation after 16:30. Recovery time of heat energy starts at 16:30 and ends at 8:30am of the following day. Of course the stored energy is not sufficient for the whole time cycle.

The performance analysis of each tank during charge and discharge periods is an unsteady heat transfer problem. Therefore the temperature of the contents of the tanks during these periods is variable. As a result, the amount of the input or output energy of the water tank and PCM tank, in an unsteady process is calculated by the following equations respectively [7]:

$$Q_w = -\int \rho c \left[T(r,\ t) - T_i \right] dV \tag{3}$$

$$Q_p = -\int \rho c \left[T(x,\ t) - T_i \right] dV \tag{4}$$

where ρ and c are density and specific heat capacity of the materials storing the heat, $T(r,\ t)$ or $T(x,\ t)$ are temperature distribution functions in the storing mediums, T_i is the initial tanks temperatures and V is the volumes of the storage materials.

If the process continues until $t = \infty$, maximum transferred energy, Q_0, would be defined as below:

$$Q_0 = \rho c V (T_i - T_\infty) \tag{5}$$

where, T_∞ is the working fluid temperature. Assuming negligible temperature drop during the charging periods of the tanks, T_∞ is assumed to be the working fluid temperature at the outlet of solar collectors. However, during tank discharge, T_∞ is the minimum temperature of the working fluid dissipating heat to the room.

The water storage tank in this research is exactly similar to 180 liters tanks used in common solar water heaters. These tanks are cylindrically shaped with diameter of 50cm and length of 90cm. The working fluid flows in the external jacket of these tanks transferring heat to the internal medium. The PCM storage tank is a compact heat exchanger with PCM between the tubes. There are 24 aluminum cylindrical tubes in the exchanger. Each tube has 20mm external diameter and 315mm length. The tubes are located in 3 rows with 65mm gap between the rows. The distance between each two adjacent tubes is 20mm (Fig. 2). With

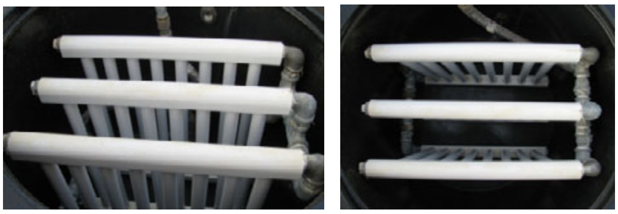

Fig. 2 Two views of PCM tank before filling

this assembly, it has been assumed that the PCM tank consists of four plane PCM walls. It is possible to store 63 liters of PCM in the exchanger. The working fluid passes through these tubes and transfers the heat to PCM or it absorbs it from the medium. PCM heat exchangers are described in some references [8].

The solutions of Eqs. (3), (4) integrals for a cylinder (water tank) and a plane wall (PCM tank) respectively are as follows [9]:

$$\frac{Q}{Q_0} = 1 - \frac{2\theta_0^*}{\xi_1} J_1(\xi_1) \tag{6}$$

$$\frac{Q}{Q_0} = 1 - \frac{\sin(\xi_1)}{\xi_1} \theta_0^* \tag{7}$$

where $\theta_0^* = C_1.exp(-\xi_1^2.F_O)$, ξ_1 is the positive root of equation $\xi_1.tan(\xi_1) = Bi$ and C_1 is a coefficient in terms of Biot number, Bi [7]. In these equations J_1 is Bessel Function and F_o is Fourier number.

On the other hand, tanks' temperature distribution at the end of each charging or discharging interval for a cylinder (Water tank) and a plane wall (PCM tank) is calculated by these equations respectively [9]:

$$\frac{T - T_\infty}{T_i - T_\infty} = \theta_0^*.J_0(\xi_1\, r^*) \tag{8}$$

$$\frac{T - T_\infty}{T_i - T_\infty} = \theta_0^* Cos(\xi_1\, x^*) \tag{9}$$

where $r^* = r/r_o$ and $x^* = x/L$ are the dimensionless distances, T is the temperature at each point and J_0 is the Bessel Function.

It should be mentioned that during the phase change period temperature is constant. So, the Lumped Capacitance Method was used for heat transfer analysis during melting or congealing. In Lumped Capacitance Method, transferred energy can be calculated by the below equation [7]:

$$Q = (\rho.\ V.\ c).\ \theta_i \left[1 - \exp\left(-\frac{t}{\tau_t}\right)\right] \tag{10}$$

where, $\theta_i = T_i - T_\infty$ and τ_t is the thermal time constant. More details about heat transfer analysis of the problem have been discussed in [5]. Since the outlet temperature of the collectors varies during the day hours, the value of T_∞ is not constant during the charging process. In the same way, at the time of discharge and with respect to the variation of the outdoor temperature, the space heat load is variable. Therefore, T_∞ is never constant during the course of time, and the solution of the problem is somewhat complicated. With respect to the complexity and parametrical nature of the problem, six separate computer programs have been devised to calculate the storable/recoverable energy in/from storage tanks and correlate these values during the time period. These six computer programs are developed by MATLAB 7 and linked to each other to obtain the stored/recovered energy in any time period. Figure 3 shows a schematic diagram of these computer programs correlations. The assumed period in this research is the six cold months of the year, from November 1st, through April 30th.

3. OPTIMIZATION

Flexibility in choosing the best available storage medium on the basis of the solar collectors' outlet temperature will increase the charging chance during the day. On this basis, the optimized state of the system performance had to be found. Since the system has two storage tanks, there are two choices for energy storage: Water tank or PCM tank. This raises the questions that how long each tank should be charged and what will be the sequence of charging each of these? Similar questions should be considered for the recovering process too. These answers are named "time schedule". Because of different solar radiation and weather condition, the schedule will vary from day to day. In other words, after the optimization process, different storage time schedules for each day of the assumed period will be obtained. For example, the optimized storage time schedule for the conditions of March 26, 2007 has been presented [5].

Considering Eqs. (1 ~ 7), to recover maximum solar energy during each day, the objective function of the problem can be written as below:

$$Max\ E_{out} = Q_{wout} + Q_{pout} \tag{11}$$

In this research, to find each day's optimum time schedules, a numerical computer program was developed. The algorithm is a sweeping method that checks all of the imaginable storage time schedules in a hybrid storage system. Comparing the values of the recovered energy at the end of each day, the maximum value can be found. Therefore, the optimum relevant time schedule will be extracted.

On the basis of energy storage in one of the tanks and energy recovery from one of them, the optimized solutions can only be 0 or 1. Therefore, the optimization problem would be an integer programming. For example, if at 11 o'clock of November 30, storage in the water tank occurs, the storage time schedule, *sts*(30, 11) = 1, otherwise *sts*(30, 11) = 0. Similarly, 1 and 0 will be allocated to the recovery time schedule (*rts*).

The detailed results of the optimization process have been presented in [6]. The summarized results of the mentioned paper are shown in Fig. 4 and Table 1. As compared with an individual water tank, it is shown that

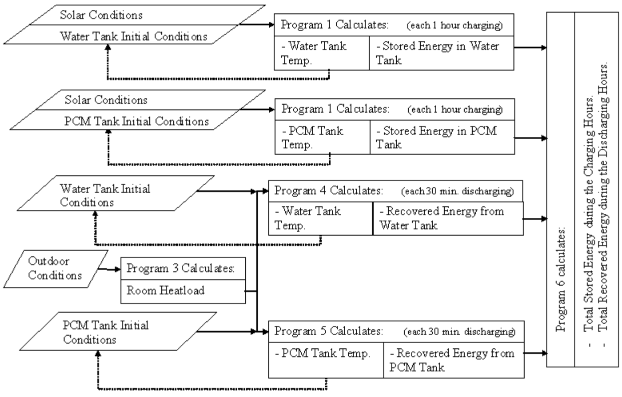

Fig. 3 Schematic diagram of six computer programs correlations

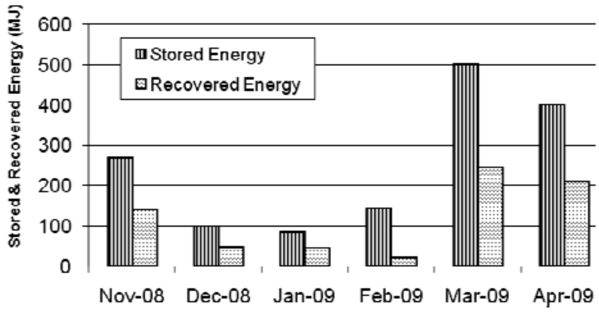

Fig. 4 Stored energy and recovered energy values, hybrid storage system

Table 1 Comparison of Optimized Hybrid System and Single Water Tank (Storage)

Month	Stored Energy in Hybrid System (MJ)	Stored Energy in Single Water Tank (MJ)	Increase (%)
Nov-2008	269.6	179.5	50.2
Dec-2008	98.9	65.3	51.5
Jan-2009	84.4	60.7	39.0
Feb-2009	143.5	145.4	−1.3
Mar-2009	502.2	423.3	18.6
Apr-2009	400.7	304.8	31.5
Sum	1499.3	1179	27.2

the assumed hybrid storage system gathers 27.2% more solar energy at the optimized point. Respectively, the energy recovery from the hybrid system also increases 23.9%. It should be mentioned that the undesirable results in February was because of the exceptional unsteady climate of that period.

4. EXPERIMENTAL ANALYSIS

In this research, storage optimization during the six cold months, beginning in November 2008 and ending in April 2009 has been considered.

One of the input data is the temperature of the working fluid at the outlet of solar collectors. This temperature was measured hourly whenever there was adequate solar radiation. For the mentioned period, solar radiation in Tehran usually begins at 8:30am and ends at 16:30pm. The summarized values of solar radiation are presented in Table 2.

The other input data is energy consumption rate at the time of the tanks discharge. This rate is actually related to the heat load of the space in different hours which itself depends on a variety of parameters such as geographical position, size of the room, construction materials and the outdoor temperature. As mentioned earlier, the space under consideration is a small office ($4.2m^2$) in the north of Tehran consisting of brick walls, 15cm thick, roof about 30cm thick, wood entrance door ($2.5m^2$), and windows with metal frame ($1.1m^2$). Table 3 shows the mean hourly outdoor temperature during the specified months.

The physical properties of water and ethylene glycol are taken from reference books [7]. Melting point of most usual paraffin waxes is in the range of 60 ~ 70°C. To achieve a PCM with proper melting point, a mixture of residue wax and slack wax was used. Residue wax is also popularly known as foots oil. This oil is produced during the production of semi refined paraffin wax. Residue wax is extensively used in tire, rubber and shoe industries. Slack wax is a mixture of oil and wax, obtained from lubricating oil. Slack wax is the crude wax produced by chilling and solvent filter-pressing wax distillate. It serves as feedstock and it is further refined and blended to create value-added petroleum wax products. In this research the mixture was made of 80% Residue wax and 20% Slack wax. In this way, the melting point was reduced to 43°C. Properties of waxes, paraffines and other organic materials have been taken from reference [10]. Properties of made mixture are given in Table 4.

The results from the theoretical analysis were verified using test data taken for the mentioned period. An acceptable agreement between theoretical analyses and experimental findings are seen for most of the days.

5. CONCLUSIONS

A method for increasing the storage capability of a solar thermal energy system has been discussed. The system included two tanks with flexibility in choosing the best storage medium on the basis of the solar collectors' outlet temperature. In this way the capacity of energy storage is increased. The results showed that using such a hybrid storage system, an increase in storable energy is obtained without increasing collectors' area. It was found that in comparison to the case of an individual water tank, the hybrid storage system stored 27.2% more solar energy at the optimized point. Respectively, the energy recovery from the hybrid system is increased by 23.9% using the same thermal collectors' area.

Table 2 Average Solar Radiation in Tehran (W/m^2)

Hour / Month	9:00 am	10:00 am	11:00 am	12:00 pm	13:00 pm	14:00 pm	15:00 pm	16:00 pm	Max.
November-2008	264	371	447	515	428	341	220	76	946
December-2008	237	353	420	428	384	322	181	63	781
January-2009	241	404	477	470	426	384	245	121	765
February-2009	296	454	469	499	443	395	321	204	986
March-2009	484	625	799	843	803	683	565	346	1172
April-2009	554	578	623	708	761	557	485	330	1276

Table 3 Mean Hourly Outdoor Temperature Variation of Tehran during the Six Cold Months (°C)

Hour / Month	0:00 am	03:00 am	06:00 am	09:00 am	12:00 pm	15:00 pm	18:00 pm	21:00 pm	Mean Daily
November-2008	7.2	6.5	5.9	10.4	11.9	12	9.1	7.9	8.8
December-2008	2.1	1.3	1.1	6.0	7.2	7.6	4.6	3.1	4.0
January-2009	1.4	0.9	-0.1	4.6	6.1	6.4	3.5	2.2	3.1
February-2009	4.7	4.2	3.3	7.2	9.1	9.6	7.4	5.7	6.4
March-2009	8.5	7.2	7.7	13.0	15.1	15.6	12.7	10.9	8.6
April-2009	9.3	8.5	8.2	13.0	14.5	15.2	13.1	10.8	11.6

Table 4 PCM Physical Properties

Melting Temperature (°C)	Density (kg/m^3)	Thermal Conductivity (W.(m.K)−1)	Specific heat Capacity (J.(kg.K)−1)	Latent heat (kJ/kg)
43	811	0.42	2804	213

For the verification of results, a small pilot system was also assembled. The comparison of the theoretical and experimental results shows a good agreement between the two.

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