DESIGN AND INVESTIGATION OF A LOW COST & PORTABLE THERMAL ENERGY STORAGE SYSTEM FOR DOMESTIC APPLICATIONS

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ABSTRACT-

In current era, thermal energy storage is a standout amongst the most proficient approaches to store the solar oriented renewable energy for warming and drying the air by energy gathered from sun. The paper exhibits a test examination of a stuffed rock bed solar thermal storage system. A 30 mm crevice is loaded with Polyester insulation in an air sealed dark painted plywood compartment from where heat can be extricated by constrained air convection. This system is able to constantly provide the required heat input into the setup. The heat decay characteristic of the bed is additionally contemplated. The most elevated introductory temperature of the rocks was recorded to 65.5 °C. Experimental result is likewise dissected by utilizing 3 thermocouples with data logger EasySense™ software. After preparatory thought of specialized, environmental and economic aspects consideration, the effective thermal efficiency of the system is measured to 63.16% with 8.814 MJ integrated energy simply following 5 hour charging period.

KEY WORDS
TES, packed bed, charging time, solar drier, specific heat capacity.

1. Introduction

With the increased demand for electrical power, the need for alternative renewable energy sources is arising. The main issues that govern the use of a particular energy source are its availability and sustainability. Natural sources of energy e.g. solar energy & wind energy are sustainable sources of energy in that they can be used but they can never be exhausted. Their availability however, is limited by weather conditions and/or climate. Most of the available renewable energy sources are incapable of providing constant power [19].

An energy bank or reservoir is needed in order to continuously benefit from the energy source even when it is no longer available. Thermal Energy Storage (TES) Systems provide this luxury. A TES can be defined as the temporary holding of thermal energy in the form of hot or cold substances for later utilization [10]. Thermal Energy Storage systems can be divided into three types of storage namely; Sensible Heat Storage (SHS), Latent Heat Storage (LHS), Thermochemical Heat Storage (THS). In sensible TES, energy is stored by changing the temperature of the storage medium. The amount of heat stored is proportional to the density, specific heat capacity, volume and variation of temperature of the storage material [14]. According to this definition, it is important that the storage medium has a high specific heat capacity. A typical sensible TES comprises of a tank, storage medium, inlet and outlet devices. This tank should be able to retain both the storage media and the heat that has been absorbed in order to prevent heat loss. Sensible Thermal Energy Storage can be classified into two: Liquid media storage and solid media storage. Liquid media includes fluids like molten salt, water, liquid metals and oil based fluids, whereas solid media includes solids like metals and rocks. Solid materials like rocks and metals can be used to store thermal energy at low or high temperatures since these materials will not freeze or boil [14].

An advantage that solid media has over liquid media is that it does not leak from its container. For solid media, cast iron is the best sensible storage media, surpassing even the energy density of water but cast iron is exceedingly expensive. The most preferred solid media are rock piles. The pebble bed or rock pile consists of a bed of loosely packed rock material through which the heat transport fluid can flow. The thermal energy is stored in the packed bed by forcing heated air into the bed and utilized again by recirculating ambient air into the heated bed [11].

The advantage of using solid-solid transitions rather than solid-liquid transitions, even though solid-liquid transitions have higher latent heat is that solid-solid phase change materials require less rigorous container requirements and better flexibility. Thermochemical Heat Storage (THS) is fundamentally based on reversible endothermic and exothermic reactions. Heat is stored during the endothermic reaction step and released during the exothermic one. The thermochemical heat stored is linked to the reaction enthalpy [16]. As with the other forms of TES, thermochemical heat storage also has its advantages. It has a very high energy density compared to the other two types of Thermal Energy Storage.
Its energy density is ten times that of Sensible heat Storage and about five times that of LHS. THS is theoretically unlimited with respect to storage period as well as transport because there is no thermal loss during storage since products can be stored at ambient temperature. Thermochemical storage systems can essentially be divided into two; open systems and closed systems.

2. Thermal energy storage system-

The open storage system is based on the adsorption process to complete the sorption processes with desiccant and heat storage systems. Closed systems work with a closed working fluid cycle that is isolated from the atmosphere. There are two processes to be defined in a closed system; adsorption and absorption (Ding, 2012). Thermochemical energy storage uses storage media like CaO – Calcium Oxide, BaO – Barium Oxide, Al2O3 –Aluminium Oxide, Na2B4O2.10H2O – Hydrous Sodium Bromate (Borax) and MgO – Magnesium Oxide. Magnesium Oxide has the highest energy density of the five thermochemical materials. Rock beds, molten salt and water can be used to store thermal energy which is then used to heat homes and buildings during winter and cold days. Solar radiation is collected using solar collectors and used to heat up the storage medium. During winter the thermal energy is used provide heat to the load. These kinds of systems can supply heat for weeks and even months depending on the application and the type of storage. Air drying systems can be incorporated with a TES system in order to improve the efficiency of the system. It can also be used to dry vegetables and farm crops in order to preserve them. TES ensures continuous supply of dry air therefore it reduces the drying time for the commodity which it is drying [17].

3. Design and methodology-

The main objective of this study is to design and construct a thermal storage system to be used with a solar air dryer along with to investigate the heat storage potential of different types and sizes of local rock materials by determining their thermal conductivity and their thermal storage capacity. The best material will then be selected. Second, to design a thermal energy storage system that can perform at 5K above ambient temperature for 8-hours with high performance and relatively good thermal efficiency.

The table 1 depicts the factors affecting the design of the entire TES. The Thermal Energy Storage system being fabricated in this particular case should be able to perform at 5°C above ambient temperature for a period of at least 8-hours. Local Rocks are irregularly shaped and therefore may not be able to supply uniformly distributed heat to the air. The table 1 outlines and explains the technical factors, design factors, environmental factors and cost factors.

This will be minimized by packing the rocks as closely as possible. A CAHO-1905 oven that was used as the source of energy for the rock samples in the experiment. It comprises of a dial thermostat to set any desired temperature between 0°C - 1000°C. Figure 1 and 2 shows the top and side view of system respectively.

<table>
<thead>
<tr>
<th>Table 1</th>
<th>Factors to be considered in the design</th>
</tr>
</thead>
<tbody>
<tr>
<td>Design factors</td>
<td>The structure must be light enough to move around and to be easily disassembled. The material should be well insulated to minimize heat losses.</td>
</tr>
<tr>
<td>Environmental factors</td>
<td>The materials used in the construction of the TES should be bio-degradable and be reusable</td>
</tr>
<tr>
<td>Technical factors</td>
<td>For high efficiency, the storage medium has to possess a high specific heat capacity and a high conductivity. The density of the medium also affects the storage capability.</td>
</tr>
<tr>
<td>Cost factors</td>
<td>The design should be affordable to the people of Botswana. Expensive materials should be avoided</td>
</tr>
</tbody>
</table>

![Figure 1](image1)

Top view of designed TES system

![Figure 2](image2)

Side view of designed TES system

Table 2 below, shows that granite has the highest conductivity amongst the five samples. The experimental results for sandstone and shale were different from the values obtained from literature. Granite and sandstone also have a high density and hence their high heat storage capacity. The average value obtained for the specific heat capacity of granite was found to be 904.3 J/kg-K.
According to literature the specific heat capacity of granite is between 790-900 J/kg-K. The average specific heat capacity obtained from the first trial was found to be 1104J/kg-K. As can be seen the first trial had a variation of 204 J/kg-K from the theoretical one. However for the second trial, the average specific heat capacity obtained varied by just 4.3 J/kg-K. This variation can be attributed to the type of granite chosen. There are many types of granite rocks in the world, each with different quartz content. The granite in the region of Botswana is not necessarily the same as the granite in other regions of the world due to differences in composition of the rocks.

### 4. Analysis

The performance of the system is tested by measuring the input heat from the sun and the amount absorbed by the rocks. The output heat was determined by measuring the temperature change before and after the exposure to the sun. The system was also tested for efficiency under different conditions like cloudy days and sunny days. The system was placed outside in the open sun from 11am to 4pm (total of 5 hours) facing North at an angle of 240. The inlet and outlet were sealed to prevent heat loss and the system was left to charge. The initial temperature before charging was measured and recorded. After charging, the system was moved back into the workshop and tested. The final temperature after charging was measured and recorded. After charging, the system was moved back into the workshop and tested. The final temperature after charging was measured and recorded. After charging, the system was moved back into the workshop and tested. The final temperature after charging was measured and recorded. After charging, the system was moved back into the workshop and tested. The final temperature after charging was measured and recorded.

### Table 1

<table>
<thead>
<tr>
<th>Rock Types</th>
<th>Mass (Kg)</th>
<th>Density (Kg/m³)</th>
<th>SHC (J/Kg-K)</th>
<th>SHC (from Lit) (J/Kg- K)</th>
<th>Heat Storage (KJ/m²-K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quartz</td>
<td>0.22614</td>
<td>2500</td>
<td>768.5</td>
<td>750-800</td>
<td>324</td>
</tr>
<tr>
<td>Rhyolite</td>
<td>0.31166</td>
<td>2300</td>
<td>92.1</td>
<td>-</td>
<td>208</td>
</tr>
<tr>
<td>Granite</td>
<td>0.03297</td>
<td>2600</td>
<td>904.3</td>
<td>800-900</td>
<td>1821</td>
</tr>
<tr>
<td>Sandstone</td>
<td>0.06119</td>
<td>2400</td>
<td>590.3</td>
<td>900-940</td>
<td>1247</td>
</tr>
<tr>
<td>Shale</td>
<td>0.10112</td>
<td>2000</td>
<td>345.5</td>
<td>350-390</td>
<td>699</td>
</tr>
</tbody>
</table>

The results were exported from the Easy Sense™ software to Microsoft Excel™ and analyzed. So, Area,

\[ A_{glass} = 1 \times W \]

\[ A_{glass} = (1.5) (1.0) \quad A_{glass} = 1.5m² \]

\[ I_T = 5.6383kWh/m²/day \]

Assuming the sun is up from 6am – 6pm (12hour day):

\[ I = \frac{5.6383}{12} = 469.86W/m² \]

The collector heat input:

\[ Q_i = I \cdot A \]

\[ Q_i = (469.9)(1.5) = 704.85W \]

The actual heat input:

\[ \alpha_{glass} = 0.96 \quad \text{(Absorption coefficient)} \]

\[ \tau_{glass} = 0.95 \quad \text{(Transfer coefficient)} \]

\[ Q_{i\text{actual}} = Q_i \cdot \tau_{glass} \cdot \alpha_{glass} \]

\[ Q_{i\text{actual}} = (704.85)(0.96)(0.95) = 642.82W \]

### 4.1 - The heat loss

\[ h_i = 22 \quad \text{W/m² · K} \quad \text{(Convective heat transfer coefficient of air)} \]

\[ U_g = 6.5 \quad \text{W/m² · K} \quad \text{(Heat transfer coefficient)} \]

\[ k_{air} = 0.026 \quad \text{W/m · K} \quad \text{(Conductivity of air)} \]

\[ k_{plywood} = 0.13 \quad \text{W/m · K} \quad \text{(Conductivity of plywood)} \]

\[ k_{polyester} = 0.05 \quad \text{W/m · K} \quad \text{(Conductivity of polyester)} \]

\[ U_L = \frac{1}{\frac{1}{U_g} + \frac{1}{k_{air}} + \frac{1}{k_{plywood}} + \frac{1}{k_{polyester}}} \]

\[ U_L = \frac{1}{\frac{1}{6.5} + \frac{1}{0.026} + \frac{1}{0.13} + \frac{1}{0.05}} = 6.6549W/m²-K \]

\[ T_c = 45°\text{C} \quad \text{(Steady state temperature)} \]

\[ T_a = 30°\text{C} \quad \text{(Ambient temperature)} \]

\[ Q_o = U_L \cdot A(T_c - T_a) \] (5)

\[ Q_o = (6.6549)(1.5)(45 - 30) = 149.735W \]

\[ T_i = 13.9°\text{C} \quad \text{(Average night ambient temperature) (Open Weather.com, n.d.)} \]

\[ T_o = 18.9°\text{C} \]

\[ \rho_{air} = 1.2kg/m³ \]

\[ m = \frac{Q_{i\text{actual}} - Q_o}{(C_P(T_o - T_i))} \]

\[ m = \frac{642.82 - 149.735}{(1005(18.9 - 13.9)) + 493.085} \]

\[ m = \frac{5025}{5025} = 0.09813kg/s = 4.906m³/min \]

Using density of air as an ideal gas and surface area of 1.5m², the required velocity of air is:

\[ v = m \times A \times \rho = 1.2 \quad \text{m/s} \]

Ideally to maintain a 5K temperature difference, the
Velocity of air has to be 1.2m/s

4.2. Useful energy

\[ Q_u = m c_p (T_o - T_i) \]  

\[ Q_u = (0.09813)(1000)(18.9 - 13.9) \]

\[ Q_u = 490.65W \]

\[ E_{useful} = 490.65W \times 8hrs = 14.13 \text{ MJ} \]

4.3. Finally the efficiency

\[ \eta = \frac{Q_u}{A I} \]

\[ \eta = \frac{490.65}{704.85} = 69.61\% \]

5. Result and Conclusion-

At the end of the testing period (8-hours) by the data harvest as shown in figure 3, the highest initial temperature of the rocks was 65.5\°C.

On the second day of testing, the TES was exposed to the sun for a period of 5 hours. The initial temperature of the rocks at \( t_0 = 0 \text{ hr.} \) was 63.4\°C. The corresponding ambient temperature was 30.5\°C. The TES managed to maintain a temperature difference of 5K for the 5 hours of the discharging process. At the eighth hour, the temperature difference was 2.5K. The results were significantly improved from the previous ones. This time the TES system managed to sustain the desired temperature difference 62.5\% of the time. Figure 5 below shows the range of thermal Energy Storage to maintain a 5K temperature difference above ambient temperature for an 8-hour period.

On the first day of the testing, the TES was exposed to the sun for a period of 2 hours 30 minutes. The initial temperature of the rocks at \( t_0 = 0 \text{ hr.} \) was 65.5\°C. The corresponding ambient temperature was 30.7\°C. The TES managed to maintain a temperature difference of 5K for the 3 hours of the discharging process.

Graph in Figure 4 shows the outlet temperature over an 8-hour period. The ambient temperature remains fairly constant. At the eighth hour, the temperature difference was 1K.

The Thermal Energy Storage system performed as desired but only for 4-hours. Though disappointing, this was not surprising because the Thermal Energy Storage system was only charged for 5-hours, i.e. from 11:00hrs – 16:00hrs. The Thermal Energy Storage system may have done better if charging was for a period of at least 10 hours, i.e. from...
08:00hrs – 18:00hrs. The system was not tested for a full day of charging. Despite this, the system performed well nonetheless and the results of the tests showed that it could perform well above its design capacity when fully charged.

Reference-


[12] IRENA, Thermal energy storage technology brief. ETSAP, 2013


