Designing a Low-Cost Thermal Energy Storage System for Small-Scale Tobacco Farmers in Zimbabwe

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Abstract

The main objective of the current paper is to design a forced convection thermal energy storage (TES) system adoptable, adaptable and affordable by small-scale tobacco farmers in Zimbabwe. The design's fabrication would comprise of locally available materials. The aim of the design is to save energy resources applied in tobacco curing processes such as solar, biogas, liquefied petroleum gas (LPG), coal, electricity, firewood, and paddy husks as is the case in Sri Lanka. Several researchers have worked to introduce new fuel sources in tobacco curing. There has also been a major focus on structural improvement of tobacco barns through raising barn interior insulation levels, selection of ideal construction materials as well as plugging all existing and potential thermal leakage points during regular maintenance. No research has been carried out focusing on introduction of thermal energy storage systems to complement other energy utilization efficiency initiatives being taken. This paper specifically designs a thermal energy storage system comprising of brickwork and a steel dome as an energy efficiency improvement measure in tobacco curing. Apart from tobacco curing, the designed TES system would be applicable to drying processes of other crops such as maize, paprika and other fruits and vegetables.

Keywords
Latent, sensible, thermal energy storage, thermochemical, thermocline

1. Introduction

The major problem is excessive deforestation due to tobacco curing in third world countries. There is high energy inefficiency where the majority of heat generated is lost or dumped. Thermal energy storage (TES) systems correct a mismatch between supply and demand of thermal energy (Muthukumar, 2021). The TES is a key technology for thermal energy utilization with growing present and future importance (Bauer et al, 2021). The current paper aims to extend TES application on a large scale in small-scale farmers' tobacco curing activities for energy conservation and resources preservation. Success of TES usage in tobacco curing will facilitate adaptation of the technology's use to other agricultural products where thermal drying is applied.

1.1 Objectives

Thermal Energy Storage (TES) system's use in tobacco curing is aimed to improve product quality, raise production efficiency and attain fuel savings for farmers. Introducing TES system would tap into energy being lost in tobacco curing due to high process inefficiencies and dumping of excess energy. TES reduces fuel resource consumption. The TES extracts thermal energy from the furnace through a charging process when the barn's thermocouple cuts off the tobacco barn interior. This is because tobacco barn's heat supply is continuous and it does not cease unit the end of the process. Energy stored inside the TES would discharge into the barn at designated times such as during nighttime to allow for workers' rest and fuel savings.

2. Literature Review

TES is used in numerous commercial and industrial applications, often integrated with solar and conventional energy sources to achieve major reliability (Cascetta et al, 2015). TES system charges, stores and discharges, storing heat for later use as well as managing to decouple between power required by the users and a solar field (Cascetta et al, 2015). Table 1 shows that 16 percent of the energy generated during tobacco curing is used in the process with the bulk constituting 84 percent lost due to very high inefficiencies (Jayasinghe and Namal, 2010). An inefficient Zimbabwean traditional tobacco barn consumes approximately 43m³ of fuel wood. This is equivalent to 15 000kg of firewood per year used to produce 1 400kg of cured tobacco (Musoni et al, 2013).

Table 1 Energy expended during tobacco curing (Jayasinghe and Namal, 2010)

Item	Quantity
Green leaf weight	3 500kg
Cured leaf weight	525kg
Removed moisture	2 975kg
Moisture removing heat	7 810MJ
Barn heat output	49 239 MJ
Barn efficiency	16 percent

Sri Lankan tobacco industry faced several paddy husks related challenges including uneven heating, removal of high quantity of ash, paddy husk sourcing, prolonged curing period and regular ducts replacement (Jayasinghe et al, 2010). Millions of trees are cut down annually for tobacco curing, which contributes to global warming, high production cost and divides tobacco quality in firewood curing barns into several grades affecting the farmers' net profit (Noor et al, 2017). These challenges prevail in Zimbabwe also including that farmers often use mouth or manual fanning for blowing the furnace to increase the heat intensity. Fatigue creeps on farmers who sometimes fall asleep only to wake up when the fire is gone degrading the product or with the barn on fire. To solve problems encountered by small-scale tobacco farmers, it is imperative to develop a TES system to alternate energy provision with conventional furnaces irrespective of the fuel type used. Figure 1 shows several physical and chemical thermal energy storage systems. TES systems increase system reliability due to reduction of energy generation peaks and raise capacity because of reduced generation costs. Excess generation in low demand periods charges the TES system avoiding energy dumping thereby increasing generation capacity during high demand periods (Muthukumar, 2021). TES enables improved thermal management, reduces the sizes of subsequent components such as boilers, condensers, evaporators and turbines (Bauer et al, 2021). Physical processes are sensible heat and latent heat (Cascetta et al, 2015).

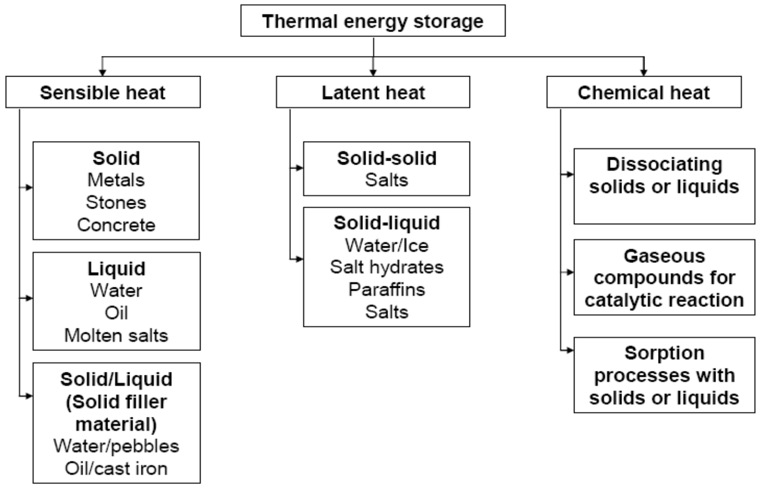

Figure 1 Classification of the three TES systems by physical phase and chemical reaction type (Bauer et al, 2021)

Latent heat is physical phase transformation of storage phase change materials (PCM) from solid to liquid and vice versa as shown in Figure 2 (Bauer et al, 2021). PCM materials work by solidifying to release heat energy and absorbing heat energy through liquefying (Nader et al, 2015). Heat absorption or release occurs at constant temperature with heat not sensed thereby being latent. Stored energy is equivalent to the heat (enthalpy) for melting and freezing (Bauer et al, 2021). Thermochemical heat storage is based on reversible thermochemical reactions. Energy is stored in chemical compounds created by an endothermic reaction and recovered by recombining the compounds in an exothermic reaction. Heat stored or released is equivalent to the heat (enthalpy) of reaction (Bauer et al, 2021). Latent heat and chemical energy technologies are most promising but technological and economic aspects make sensible heat superior and most common way of TES (Cascetta et al, 2015).

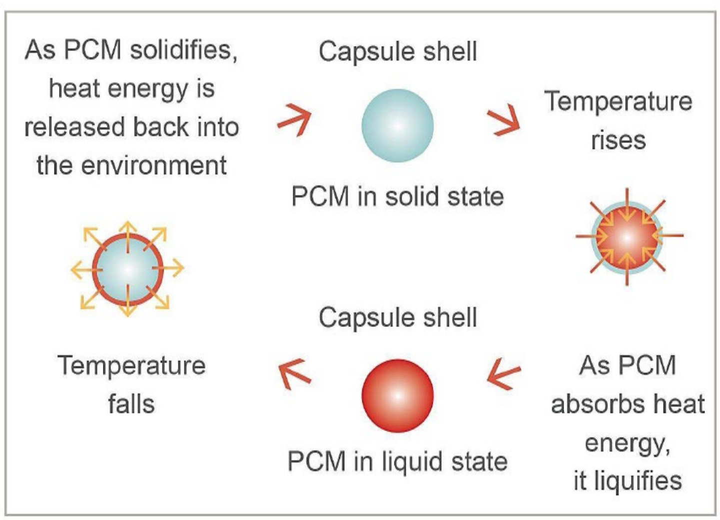

Figure 2 Latent heat PCM heat transfer and storage processes (Nader et al, 2015)

Sensible heat storage (SHS) of liquid or solid material represents the simplest and least expensive TES system, making it the most developed and commercialized (Prasad et al, 2019). The design is a sensible heat tobacco curing TES system. Requirements for sensible heat are high thermal capacity, high melting point, high thermal conductivity and low cost (Muthukumar, 2021). Sensible thermal energy stored by the TES depends on the medium's heat capacity, temperature change, and storage material amount (Sreekumar, 2007). For a temperature difference ΔT = T2-T1, this heat or enthalpy amounts to $Q_{sensible}$.

$$Q_{sensible} = m \cdot c_p \cdot (T_2 - T_1) = m \cdot c_p \cdot \Delta T \quad (1)$$

or through integration:

$$Q = \int_{T_1}^{T_2} m C_p \, dT = m\, C_p\, (T_2 - T_1) \quad (2)$$

where m is the mass of the heat storage medium (kg), C_p the specific heat capacity (J/kg°C) and T_1 (initial charging temperature) and T_2 (final charging temperature) represent respectively the lower and upper temperature levels (°C) within which the storage operates. The difference (T_2-T_1) is called the temperature swing. Sensible heat materials are water, heat transfer oils, inorganic molten salts, as well as rocks, pebbles and refractories. Solid material is invariably in porous form and heat is stored or extracted by gas or liquid flow through pores or voids (Sreekumar, 2007). In designing the tobacco curing TES system, the study applies packed bed with rocks and air heat transfer fluid (HTF).

2.1 Sensible Heat Solid Storage Media

Prasad et al (2019) cite that solid materials including metals, concrete, rocks, sand and bricks are used for high and low temperature energy storage because they neither boil, freeze nor encounter high vapor pressure as water and other liquid drawbacks. Their operating pressures are close to ambient, removing pressure-containing vessels and leakages. Solid TES media cannot be circulated easily and are used as passive storage, with a fluid mainly air being used as a HTF in and out of the sensible storage tank. Direct contact between the HTF fluid and the solid maximizes heat transfer efficiency during charging and discharging. Storage material temperature is reduced by the discharging process, resulting in decline of HTF temperature over time. Microbial activity in warm, moist environment introduces difficulties. Solid storage is mostly used in low-temperature applications including industrial waste heat recovery and space heating. Solid SHS materials also have a low energy density, except of costlier cast iron with an energy density exceeding that of water and taking a longer period to profitability. Due to low cost, rock piles and pebble beds are the most used materials (Prasad et al, 2019).

2.2 Sensible Heat Storage in Rocks

Pebble beds are usually employed for energy storage in air systems (Kalogirou, 2014). Use of low-cost filling materials in a thermocline system based on a single-tank loosely packed bed reduces TES section and heat transfer fluid volume (Cascetta et al, 2015). Heat transfer is efficient due to the large surface area over which the air comes into contact with the rocks. Advantages of rocks are easy availability, very low cost, non-flammability, and lack of toxicity (Prasad et al, 2019). Limitations are the lower volumetric heat capacity and thermal conductivity of air compared to thermal oil and molten salts, a higher air mass flow rate where a large surface area are required, with higher pressure drops and energy losses. Energy stored in rocks depends on thermo-physical properties of the solid media, its packing density, shape and size of particles, and the HTF used. Geometric and thermal properties of packed beds are described in terms of the void fraction, particle size, the cross-sectional area and length of the bed, Reynolds number and superficial air velocity. A capacity of 300 to 500 kg rock/m^2 is considered as a reasonable area for space heating application. Rocks store about 36kJ/kg, for a temperature difference of 50°C (Prasad et al, 2019).

When charging the TES system, the heat transfer fluid (HTF) hot air enters the top of the storage unit and heats the distribution of the pebbles with high temperature at the top and low at the bottom (Kalogirou, 2014). Charged hot air is circulated through the gaps between the rocks (Prasad et al, 2019). High temperature zone in the upper part of the tank is separated from a low temperature zone in the lower part of the tank, by a temperature gradient or thermocline that moves downwards (Cascetta et al, 2015). During heat demand, hot air discharge from the top of the unit and cooler air is returned to the bottom of the unit, causing the bed to release its stored energy (Kalogirou, 2014). This flow reversal through the cold HTF pumped from the bottom of the tank causes thermocline upward movement (Cascetta et al, 2015). Charge and discharge processes alternate, with rocks and air changing temperature in the direction of airflow and temperature differentials existing between the rocks and air (Kalogirou, 2014). Figures 3 and 4 show an experimental set-up for testing a sensible heat TES system performance (Cascetta et al, 2015). The TES system was made up of a carbon steel tank filled with freely poured alumina beads permitting investigations of heat transfers in packed beds. Tests revealed influence of operating conditions and physical parameters on thermocline formation such as thermal behavior of TES system in repeated charging and discharging processes. Better charging efficiency was observed for lower values of mass flow rate, maximum air temperature and increasing aspect ratio (Cascetta et al, 2015). The current study designs a TES system to charge, store and discharge tobacco curing thermal energy. Air HTF-based beds packed with rocks sensible heat systems eliminate temperature or pressure devices and requirement for a heat exchanger between the HTF and the storage medium (Cascetta et al, 2015).

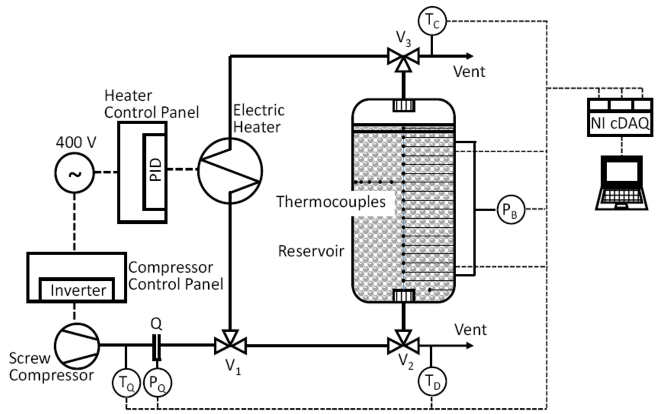

Figure 3 Schematic of packed bed sensible heat experiment set-up at Cagliari University, Italy (Cascetta et al, 2015)

Cascetta et al (2015) cite that owing to the temperature gradient, thermocline systems are less efficient than two-tank systems because of the presence of an unexploited zone of the tank and the progressive reduction of the useful energy during continuous operation due to thermal hysteresis. For the tobacco curing design, the thermal hysteresis deficiency is overcome by prolonging the storage stage and shortening the charge and discharge stages Stored energy depends on mass flow rate, temperature thresholds, inlet-outlet temperature difference, aspect ratio (length to diameter ratio L/D), void fraction and particle diameter (Cascetta et al, 2015).

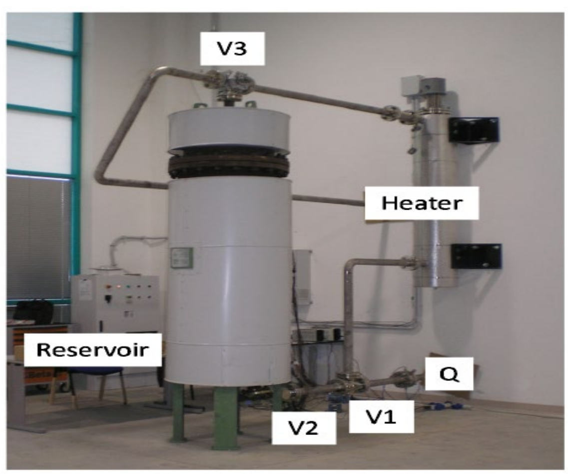

Figure 4 The packed bed experiment's laboratory test rig at Cagliari University, Italy (Cascetta et al, 2015)

3. Methods

The methodology being pursued designs a TES similar to the above Cagliari sensible heat TES pebble bed and Lleida PCM experiments (Farre, 2016). The design is an arched brick walled thermal energy storage. ArchiCAD 16 architecture software is applied in the design process. Smirnov (2015) explains operational characteristics of ArhiCAD as a complex tool of full project creation as it is able to connect exterior and interior designs to one picture. ArchiCAD can prepare all drawings, specifications and other required construction lists for engineers. A survey by Smirnov (2015) shows that it is used by 30% of architects comprising of the majority as shown in Figure 5.

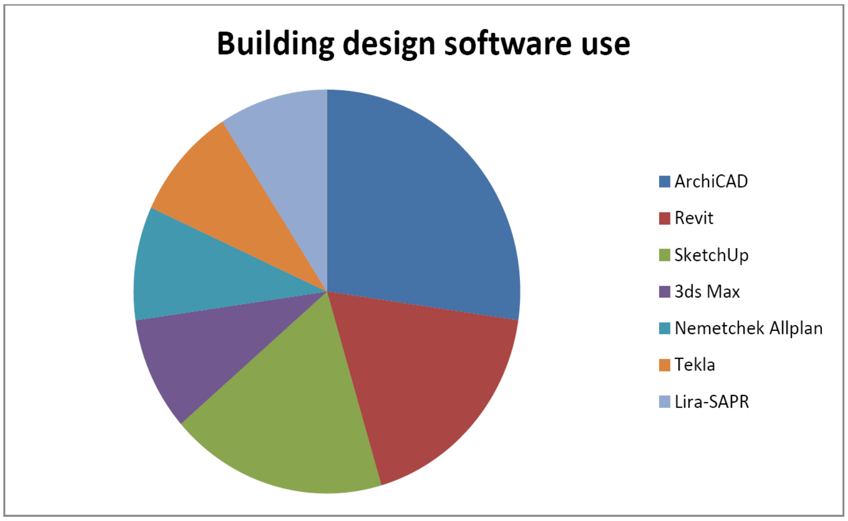

Figure 5 Comparison of architectural design software use (Smirnov, 2015)

Smirnov (2015) cites that the conception of ArchiCAD is that the user creates the 3-dimensional (3D) model building through tools that have analogues in real life such as walls, columns, doors and windows. After completion, the program allows extracting various information from the projects such as floor plans, facades and sections. The main advantage of ArchiCAD is the interaction between all parts of the project. The technology enables working with separate drawings for the whole project (Smirnov, 2015). There is also easier interoperability with other software such as importing documents from AutoCAD planning, then AcrhiCAD designing or modelling and finally exporting into Artlantis (Smirnov, 2015)

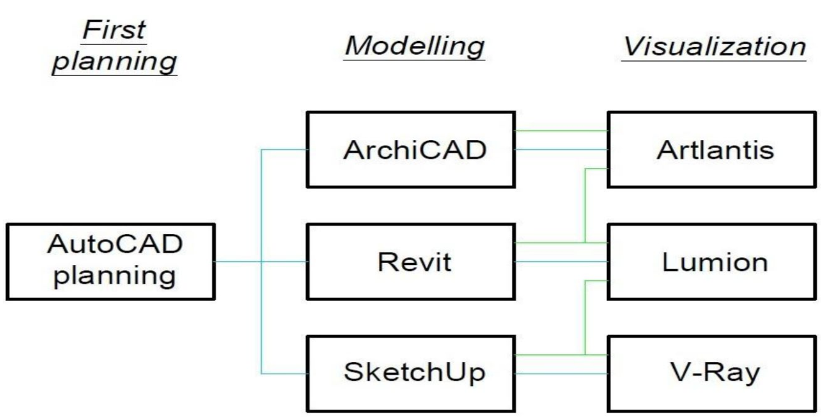

Figure 6 Scheme of software interaction (Smirnov, 2015)

In the AchiCAD design, the thermal energy storage system (TES) is made up of a cubic brick wall and a steel dome. The brick wall accommodates the heat storage materials in form of rocks. The steel dome at the top accommodates the rest of the TES access and exit connection points. Locally available bricks are used for construction. Abundant rock pebbles are the heat storage medium to fill in the storage facility. The design can either retrofit into existing tobacco barns or clad into any new tobacco barn constructions in order to achieve structural integration and save on building materials. The design integrates the brick wall, a steel dome and its hoist gantry system.

4. Data collection

Data collection comprises of detailed component design. Data of dimensional specifications is used in the design process. The major components under design details are the brickwork, the arched steel dome, system insulation, dome hoist gantry system and electrical power drives and controls. Under each component design are the required dimensions and performance characteristics to be achieved.

4.1 Brickwork

Figure 7 The alveolar brick TES test structure at Lleida University in Spain (Farre, 2016)

Figure 7 shows an alveolar brick cubicle constructed to test both phase change materials (PCM) and non-PCM TES systems at Lleida University in Spain (Farre, 2016). Figure 8 is the artistic view of a similar complete TES system under the current design. The semi-circle of ½-metre radius crest made up of 23cm brickwork is built on each of the shorter sides continuing from the 3m height of the main cubicle wall. The brick wall is reinforced by 23cm wide brick-force linings at every 4-course interval and internally plastered. A layer of 23cm wide damp course is laid between the foundation and the brick wall. Arching increases TES system's storage volume from 3m³ to 5.3565m³.

Figure 8 Artistic impression of the complete TES design set up

Figure 9 is the floor and wall layout of the current design of brickwork for a structure and materials similar to the above setup, with all dimensions at foundation and structure height shown. Internal dimensions of the TES brick cubicle are 3m × 1m × 1m. The foundation consists 4-layer × 23cm brickwork below the ground level. The floor concrete will be 6cm thick.

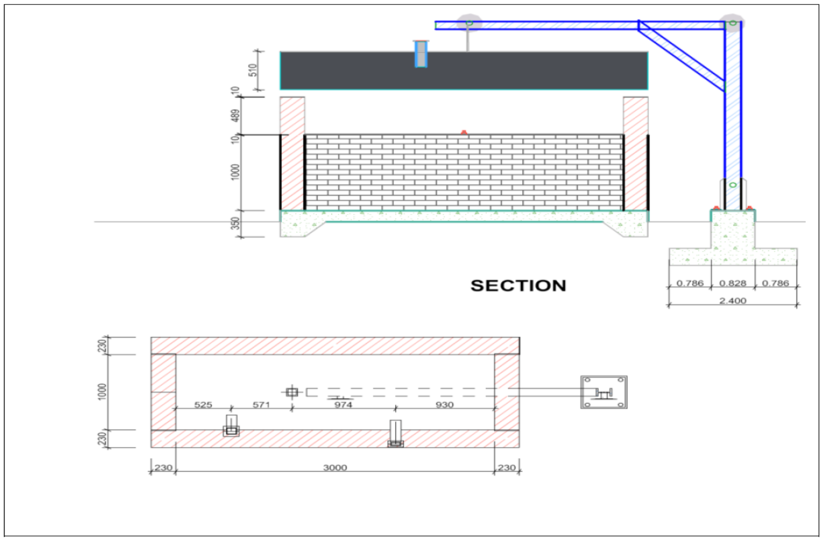

Figure 9 Cross-section of the structure foundation and walls

4.2 The Arched Steel Dome

Figure 10 is the design's side view showing the position of fitting the semi-circle dome at the top of the TES structure. The dome will be made of mild steel material and have three nozzles respectively for feeder inlet inclined at 60° at the structure contact, delivery outlet inclined at 30° at contact and pressure relief valve fitted vertically at the top through precision welding. Both the feeder inlet and the delivery outlet will have air filters fitted into the design for dirt and moisture removal. The dome arch will traverse an arc of length ½ × π × d = ½ × 3.14 × 1m = 3.14÷2 = 1.57m. Allowing for overlaps and tolerances on both ends, a 2m × 3m × 3mm thick mild steel sheet material is to be procured, shaped into a dome and installed. The ends of the dome cap will have a cast iron bar lining with a set of six by 25mm holes on two longer straight sides to facilitate its bolting on the brick wall for the TES system.

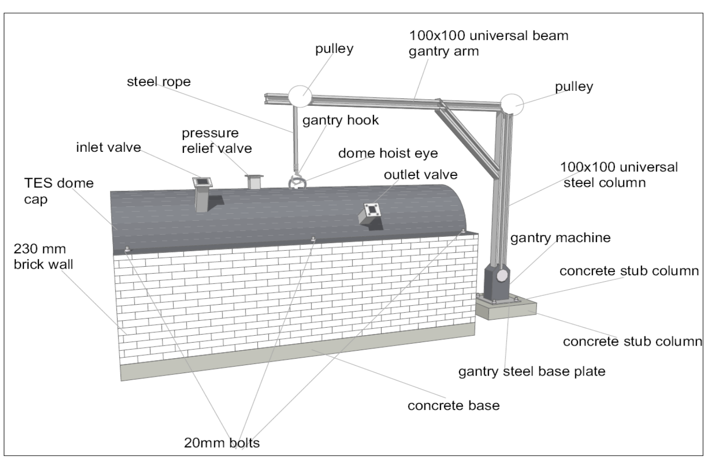

Figure 10 Side view of the TES system

4.3 System Insulation

Both the main brickwork structure' wall and its dome will have a 3mm sealant gasket lining to provide for an airtight contact surface between them to prevent air leakages from taking place. Table 2 shows thermal properties of concrete, bricks and steel as good thermal conductors with high specific heat capacity henceforth demanding strong TES system interior thermal insulation.

Table 2 Commonly used sensible solid materials (Muthukumar, 2021)

Storage medium	Operating temperature, °C	Heat capacity, kJ/kg-K [k]
Reinforced concrete	400	0.85 [1.5]
NaCl (solid)	500	0.85 [7]
Cast iron	400	0.56 [37]
Cast steel	700	0.6 [40]
Silica fire bricks	700	1.00 [1.5]
Magnesia fire bricks	1200	1.15 [5]

Low cost — High thermal conductivity and volumetric storage capacity

The TES feed and delivery piping systems are also thermally insulated to prevent heat transfer losses from occurring. Thermal insulation is used by the building industry to reduce the heat loss or gain through the house envelope including walls, windows, roofs and foundation (Hassan and Khan, 2016). R-value refers to the ability of insulation material to resist heat flow (Hassan and Khan, 2016). R-values vary depending on the heat flow direction through the product, with higher R-value insulation yielding better results in thermal performance (Hassan et al, 2016). Table 3 gives R-values for selected insulating materials. The ideal thermal insulator considering highest R-value would be polyisocyanurate but the most appropriate is polyurethane foam because it can be spray painted within the TES system structure's walls' interior, floor and dome cap interior. Paints with high polyurethane content in chemical composition will be used for insulation spray painting. This follows a one-coat varnishing applied to the structure interior.

Table 3. R-value of different materials (http://www.washington.edu, 2021)

Materials	Thickness(mm)	R-value
Expanded Polystyrene (Extruded)	25.4	5.00
Polyurethane Foam (Foamed on site)	25.4	6.25
Polyisocyanurate (Foil Faced)	25.4	7.20

4.4 Dome hoist gantry system

For mounting, servicing, repairs and maintainability off-season pre and post-harvest period, a fixed two-pulley system gantry hoists the dome through an eye welded at its center. The gantry has a 300-kilogram hoist capacity. Hoisted dome mass in kilograms = $l \times b \times h \times \rho = (200cm \times 300cm \times 0.5cm \times 8) \div 1000 = 240kgs$. Dome metal's length, l = 300cm, b = 200cm, h = 0.5cm and steel density, $\rho = 8g/cm^3$ (Alphamedia.net, 2021). Steel density varies depending on the alloy components, but generally ranges from 7 750 to 8 050 kg/m^3 or 7.75 to 8.05g/cm^3 as calculated by dividing the mass by volume (Alphamedia.net, 2021). Hoist capacity tolerance provision of additional 60 kilograms caters for other apparels pitched on the dome such as feeder inlet, delivery outlet and pressure relief ducts. The fixed gantry can be reconfigured to manual or automated operation and also wheel mounted to remove redundancy in order to perform multitasks for handling more cargo at the farm. Figure 11 shows the hoist gantry system under use through lifting and positioning the steel dome into its place at the brickwall.

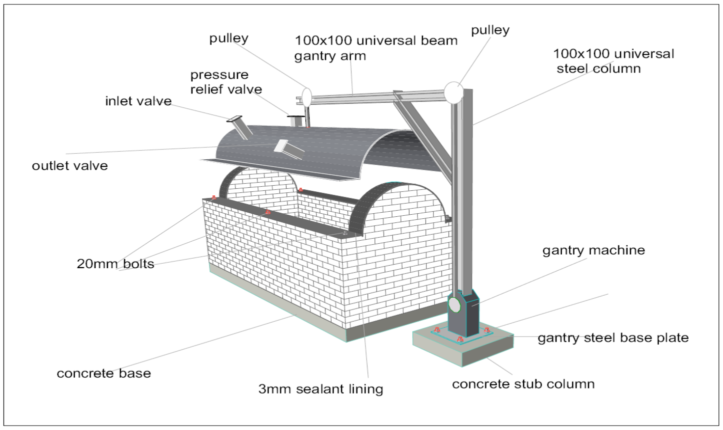

Figure 11 Fully labelled diagram of the complete TES design

4.5 Electrical Power Drives and Controls

Although the design will be tested through use of conventional electricity, photovoltaic (PV) and diesel generator sets are alternatives for remote rural areas. This is because PV penetration in previously marginalized remote rural areas in the developing world including Zimbabwe is extremely high. A PV system comprising of 4 X 330 watt panels and other components such as storage batteries, MPPT inverter, cabling and switches will manage the electrical energy requirements for drives and controls.

5. Results and Discussion

Results discuss the operational functionality of the designed TES system. All TES components are shown and labelled in Figure 11. Locally available rock pebbles with voids and pores for airflow will be laid in the TES bed, creating the requisite sensible heat storage medium. Rock filling will be at 0.45 void ratio in the rectangular bed and storage air only in the dome space. The TES system will operate through both forced convection and natural convection. When the tobacco barn cuts off the heat supply from the furnace at attainment of its required temperature level, the active heat source furnace then diverts the thermal energy to the TES system through the 750-watt blower and the feeder inlet duct in a charging process. When the tobacco barn requires more heat, the storage discharges stored heat into the barn through the TES discharge delivery outlet using furnace conduit. The furnace will be off while the TES supplies heat. Endurance of the TES system in terms of time and amount of heat delivered is then measured with corrective action taken because these parameters determine the period which the furnace can be shut down to save energy and fuel resources. The designed TES system is adaptable to both solar thermal and conventional heat energy sources.

5.1 Numerical Results

The designed project will translate into costs at implementation to test performance characteristics. The bill of materials and estimated project costs are presented. This is because similar to any other engineering project, the tobacco curing TES requires an investment. Table 4 shows the bill of materials and estimated total investment for the experimental project. The brickwork and its finishing are expected to cost US$1 000 and the dome with its apparels costing US$1 500. The total project cost is US$2 500. Total investment can be brought further downwards upon applying competitive bidding by prospective suppliers without compromising quality which is purchase to best advantage. Construction and heat storage materials are locally available. Costs will be reduced where part of the infrastructure such as fireplace or fuel exists already. Farmers can invest in the brickwork during the first year and the arched dome cap with ancillaries for mounting in the second year or alternatively on trade or credit terms. Assuming an annual yield of 1 500kg sold at US$2 per kg, the farmer's earnings will be US$3 000. At a profit of US$800 per year, the farmer's payback on the investment is expected to be 3 years. The farmer's biggest benefit is the reduction of fuel consumption as the thermal energy storage facility complements the conventional heat source to deliver tobacco curing energy. Measurable fuel savings accrued through raised efficiencies will be factored into the payback.

Table 4 Bill of Quantity and cost estimates

A. Brickwork structure			
Materials	**Calculated quantity**	**Est. unit cost in US$s**	**Est. total cost in US$s**
Wall length bricks	14 x 13 x 2 = 364		
Foundation length bricks	14 x 4 x 2 = 112		
Wall breadth bricks	5 x 13 x 2 = 130		
Foundation breadth bricks	5 x 4 x 2 = 40		
Two breadth arches	5 x 7 x 2 = 70		
Total bricks	716		
Order (minimum)	1000	100	100
Cement	20 bags x 50kg	15	300
Pit sand	$5m^3$ x 1 load	60	60
River sand	$5m^3$ x 1 load	60	60
¾ quarry stones	$5m^3$ x 1 load	60	60
Damp course	1 roll x 20m	5	5
Brick force	5 rolls x 20m	5	25
Rock-pebble freight	1 round trip	50	50
Insulation materials	1 complete set	40	40
Labour	Builder and assistant	150	300
Subtotal A			**1 000**
B. Arched light steel dome and mounting			
Materials	**Calculated quantity**	**Est. unit cost in US$s**	**Est. total cost in US$s**
Arched steel	2m x 3m = $6m^2$	120	360
Nozzles, bolting & welding provision	3 nozzles and hoist eye	60	180
Dome fixtures	Spindle & iron bars	180	180
Blower fan, piping/ducting	1 complete set	200	200
Heat source and fuel	1 complete set	200	200
Insulation materials	2 complete sets	40	80
Measurement instruments	1 complete set	200	200
Two-pulley gantry hoist system	1 complete set	100	100
Subtotal B			**1 500**
Estimated total investment on the project			
Subtotal A			1 000
Subtotal B			1 500
Estimated total cost			**2 500**

5.3 Proposed Improvements

Improvements suggested are that the project is scalable. Scalability will comply with similitude whereby it is an exact replica of any other design to all dimensions. Two objects are said to be geometrically similar if all linear length scales of one object are a fixed ratio of all corresponding length scales of the second object (McDonough, 2009). Also, two geometrically similar objects are said to be dynamically similar if the forces acting at corresponding locations on the two objects are everywhere in the same ratio. We require geometric similarity in order to even consider dynamic similarity and fulfil the design's airflow system (McDonough, 2009). Therefore, it is a one-size fits to tobacco barns.

6. Conclusion

An ideal $5.3565m^3$ sensible heat thermal energy storage system was designed for use by small-scale tobacco farmers during curing of their crop. It is meant to complement energy-efficiency measures being undertaken by other researchers. With a total investment of US$2 500 which can be undertaken in phases for two years and all building materials locally available, the project is implementable and recommended. The benefits are the energy and raw fuel resource consumption reduction, deforestation reversal, marked success in agroforestry projects as well as the greenhouse gas emission reduction. The heat storage material are rock pebbles which are in abundance for free in the exception of the transportation costs. There will be marked improvement in product quality as barns begin to receive consistent heating for desired energy levels. The project attains a quick payback time and profitability and it has got a lifetime of 20 years with minimum maintenance.

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