

Phase change material selection for small scale solar energy storage systems

^aWeyers S.J., ^aSebitosi AB. ^bOkou R.

^aCenter for Renewable and Sustainable Energy Studies, University of Stellenbosch
Matieland 7600 Rep. of South Africa

^bDepartment of Electrical Engineering, University of Cape Town Rondebosch 7700 Rep. of South Africa

Email:Sebitosi@sun.ac.za

Abstract

This paper focuses on choosing an appropriate phase change material for latent heat storing systems that can store excess energy of a small scale solar thermal power plant suitable for distributed or off grid power supply. Most commercially available thermal storage materials cater for Mega Watt scale power plants operated by utilities and hardly any attention has been paid to small-to-medium consumer scale power generation.

Latent heat storage systems have the capability to act as storage media in current industries utilising thermal energy. The development and implementation of latent heat thermal storage systems within the industrial and residential sectors could lead to extensive energy and cost savings. Latent heat storage systems are comprised of two main sections including the development of a suitable heat exchanger and the selection of a substance to store thermal energy. The study undertaken is intended for applications with operating temperatures ranging from 100 °C – 140°C.

The evaluation process used to select the best material included a variety of facets that was compiled by analysing the whole life cycle of the material. These aspects comprise of the economical validity, sustainability, and material properties of a substance. The results of this study prove that latent heat storage system have the capability to serve as suitable thermal energy storage systems.

1. Introduction

Renewable energy resources are abundantly available in sub-Saharan Africa and present a great potential in addressing the energy supply challenges. The intermittent nature of these resources however, necessitates the use of a storage system. Traditionally rural energy storage systems are exclusively electrical and no appropriate thermal energy storage technologies are available.

This paper focuses on evaluating and selection of suitable locally available phase change materials (PCM) for storing solar thermal energy for small scale applications such as household thermal uses as well as possible village-based (kilo-watt-size) solar thermal power plants suitable for distributed or off grid power supply. The intended application is for thermal energy systems operating at temperatures ranging from 100 °C – 140°C. Most commercially available thermal storage materials (such as molten salt) are only suitable for Mega Watt scale power plants operated by utilities and hardly any attention has been paid to small-to-medium consumer scale power generation. Moreover the concept of storing energy in thermal form in rural sub-Saharan Africa is yet to be tested as the use of chemical batteries remains the only energy storage mode.

The evaluation process used to select the best materials included a variety of facets that was compiled by analysing the whole life cycle of the different materials. [1-3].

2. Methodology

The selection of promising PCM for the intended purpose of latent heat storage medium was initially done by evaluating current materials against a list of design specifications [4-7].

The properties in table 1 as well as the economic viability are the key parameters considered.

Table 1: Phase Change Material Design Specifications

Phase Change Material Design Specifications	
Property	Description
Thermal Properties	
Melting Temperature	Temperature at which the phase transition from solid to liquid phase occurs should be between 115 – 130 °C
Latent Heat of Fusion	Energy absorbed or released during transformation from solid to liquid phase should equal or exceed 130 kJ/kg
Thermal Conductivity	The rate of thermal energy distribution within the material should exceed 0.4 w/m.k
Chemical Properties	
Toxicity	Must be non toxic to the environment and humanity
Flammability	Should be non flammable or ignite at temperatures below 170 °C
Chemically	Must keep chemical structure during extensive cycling periods

Stable	
Physical Properties	
Volumetric change	The change in the material density between solid and liquid phase should be less than 10 %
Sub cooling	Deviation from melting point during freezing process should not be less than 1 °C
Non Corrosive	The material must not corrode or degrade the heat exchanger and encapsulation used for latent heat storage system

The thermal capabilities of the material are then evaluated by monitoring the temperature change in the material during thermal energy loading and extracting cycles [8-10].

The temperature of each material is monitored and recorded utilizing thermocouples in combination with data acquisition equipment that stores the measured results. The experimental results are analyzed to determine the storage capabilities of the material, discharge rates and chemical stability of each material. The equipment and material required to perform the experiment is listed in table 2.

Table 2: Experiment Equipment

Experiment Equipment Requirements			
Ref	Name	Description	Quantity
1	Oven	Used to heat material to predefined temperature	1
2	Porcelain square bowl	Serves as container during thermal cycles	1
3	Thermocouple	Used to measure temperature at predefined points	5
4	Thermometer	Used for reference temperature	2
5	Phase change Material	Material selected to be tested	500g
6	Computer	Used to document, analyze and interpret data from thermocouple	1
7	Scale	Determine weight of material to be used	1
8	Ice bath	Used to calibrate thermocouples	1
9	Data logger	Measure and document results	1
10	Camera	Use to capture photos of cooling material	1
11	PPE	Pair of Gloves to protect user from hot material	1

3. Test Results

3.1.1. Erythritol

The heating and cooling curves used to evaluate the erythritol are shown in figures 1 and 2. The curves represent the change in material temperature during thermal loading and discharge cycles. The average atmospheric temperatures for the oven and environment during each cycle as depicted in the graphs are shown in table 3 below

Table 3: Erythritol thermal cycling atmospheric conditions

Average atmospheric conditions for erythritol thermal cycles		
Cycle	Oven temperature	Environmental temperature
5	150.35	17.56
6	148.12	17.71
7	150.98	16.58
8	149.26	17.75
9	151.64	16.55

Figure 1 represents the heating curve of erythritol as it undergoes thermal loading. It is evident that erythritol melts constantly at 118 °C. The phase transition process also takes place in a similar manner during all the cycles. The small changes in the heating and cool gradient are due to the difference in oven temperature and can be confirmed by comparing the heating curve with the values listed in table 3.

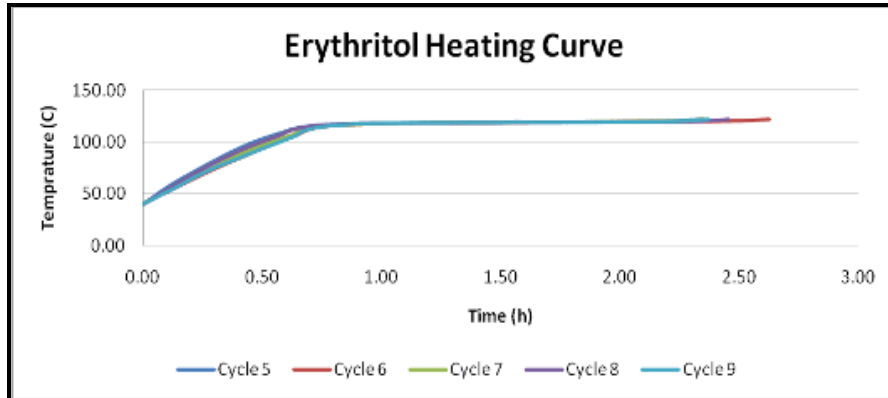


Figure 1: Erythritol heating curve comparison

Figure 2 represents the cooling curve of erythritol as it thermally discharges at the ambient environment temperature. It is evident that erythritol remains chemically stable. The change in the cooling gradient observed can be related to the change in the environmental conditions and is confirmed by comparing the values in table 3 to the curves in figure 2.

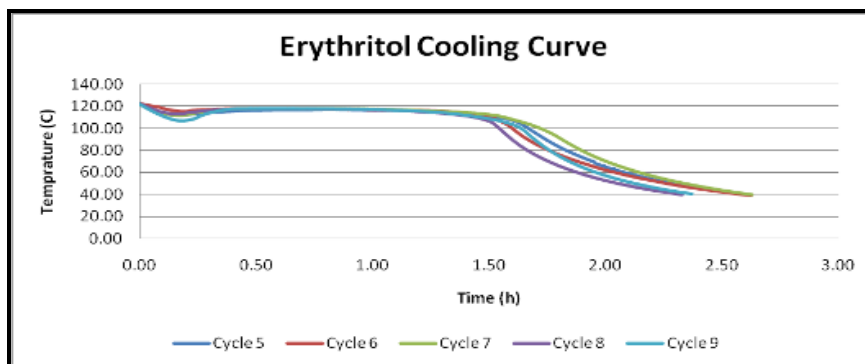


Figure 2: Erythritol cooling curve comparison

3.1.2. Magnesium Chloride Hexahydrate

Figures 3 and 4 show the heating and cooling curve for 500 g of magnesium chloride hexahydrate. The ambient atmospheric conditions for the oven and environmental temperature are listed in table 4.

Table 4: Average atmospheric conditions for magnesium chloride hexahydrate

Average atmospheric conditions for magnesium chloride hexahydrate thermal cycles		
Cycle	Oven temperature	Environmental temperature
2	151.36	17.90
3	155.23	17.13
4	152.16	17.84
5	151.25	16.26
6	151.02	14.65
7	147.4	14.13

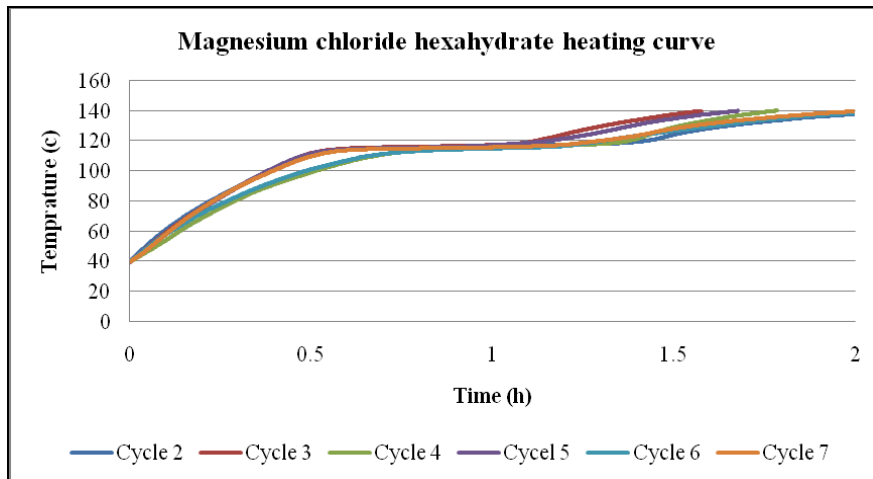


Figure 3: Magnesium chloride hexahydrate heating curve

The changes in the gradient and form of the curves are directly proportional to the change in ambient conditions of the material due to the heating characteristics of the PCM. The manner in which the material heating and cooling curve gradient changes is dependent on the difference between the material temperature and the atmospheric temperature. The difference in ambient temperature may be the major cause in the curve variation but the change observed in the material structure raises concerns about the chemical stability of the material.

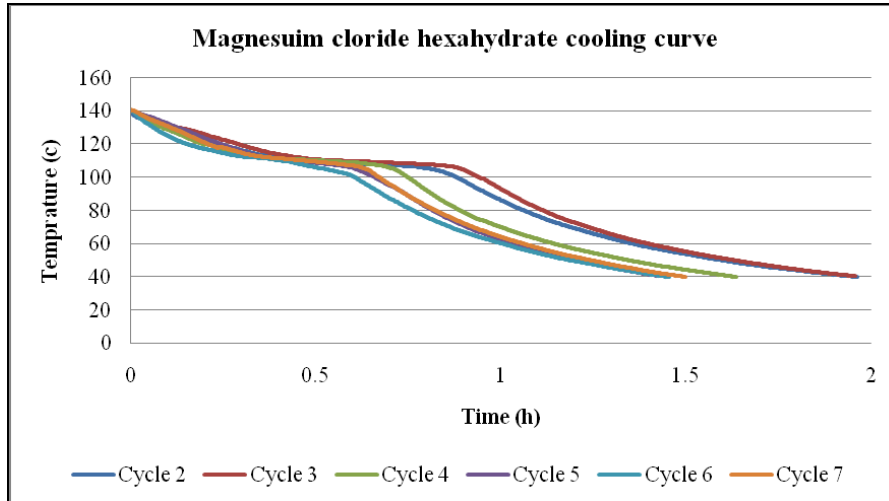
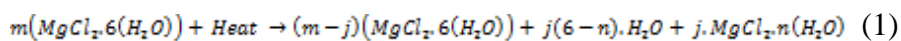


Figure 4: Magnesium chloride hexahydrate cooling curve

During thermal cycling it was observed that phase segregation occurs during extensive thermal loading that is characterized by the build up of fluid in the PCM container. This observation is confirmed by the variety literature available on magnesium chloride hexahydrate that states that the material is highly unstable and is subjected to phase segregation during thermal loading [2, 6]. The phase segregation is due to the formation of lower level salt hydrates as portrayed in equation 1.



The analysis above suggests that magnesium chloride hexahydrate experience phase segregation during thermal cycles that causes chemical instability. The change in magnesium chloride hexahydrate structure results in the decline of its thermal properties and makes it unsuited for latent heat storage systems. Erythritol proved to be chemically stable and best suited for latent heat applications from a chemical stability point of view.

3.2. Thermal Energy Extraction Test

Erythritol

A single thermal cycle for erythritol is shown in figure 5 and depicts the change in material temperature as the material is heated during

thermal loading and cooled during thermal discharge. As seen from figure 5 erythritol has the capacity to discharge its thermal energy and decrease the thermal discharge rate of the ambient oven air by supplying the air with additional energy during the cooling cycle.

The difference between the oven temperature including and excluding the PCM material can be related to the amount of energy supplied by the PCM. The amount of energy supplied by the PCM can be calculated by using equation 2 and 3.

$$Q = \int dt \cdot Q^0 \quad (2)$$

$$dQ = Q_A - Q_B \quad (3)$$

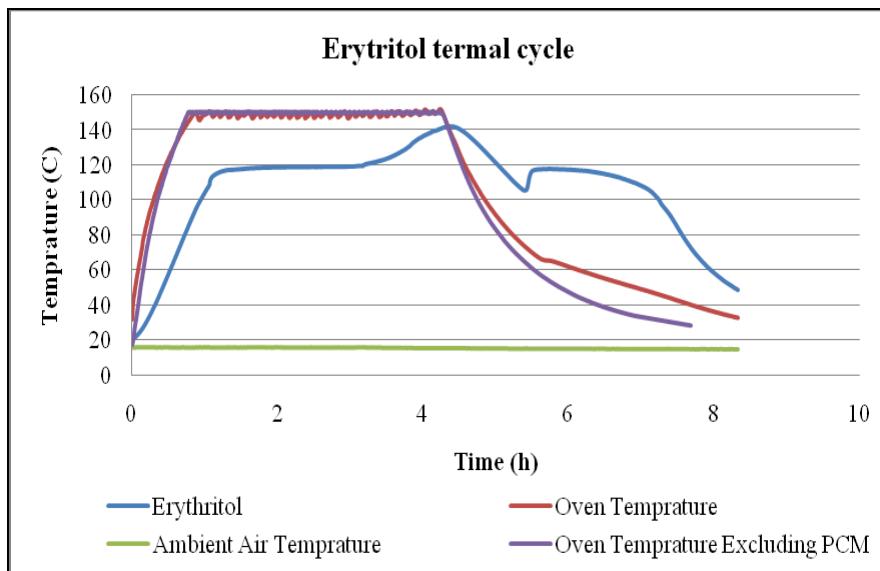


Figure 5: Erythritol thermal cycle

3.3. Self-Discharge Test

The change in erythritol temperature as it cools down while encapsulated in a crude homemade storage unit is illustrated in figure 6. The rate at which the material thermally discharges is highly dependent on the type of insulation material used to inhibit the thermal energy flow by imposing a thermal resistance.

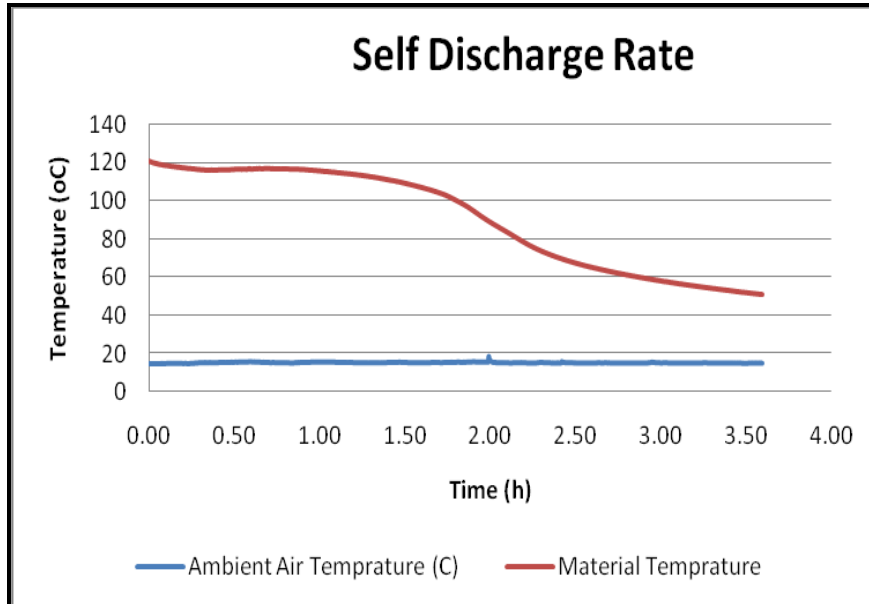


Figure 6: Self discharge rate test

The use of paper may not be the best insulation material but from figure 6 it can be seen that 500g of erythritol could stay heated above 100°C for a period of up to 2 hours. The discharge rate of the material could be decreased by the use of a proper encapsulation in combination with a suitable insulation barrier.

3.4. Thermal Properties Evaluation

3.4.1. Energy Storing Capability

The energy storing capability of a material is a combination of the materials ability to store sensible heat and latent heat. Two 1 kg sample materials of erythritol and magnesium chloride hexahydrate were tested for a temperature range of 21 – 150 degrees Celsius.

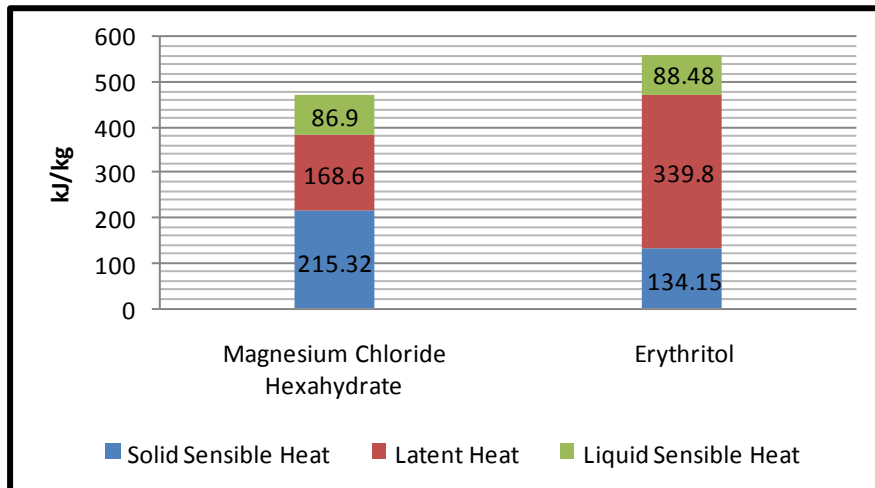


Figure 7: Materials Energy Storage Capabilities

From figure 7 it was evident that the majority of magnesium chloride hexahydrate energy is stored in the form of sensible heat but also have a smaller storage capability of that compared to erythritol.

3.4.2. Heat Transfer Rate

The heat transfer rate in the material is highly dependent on the materials conductivity, specific heat and the type of heat exchanger used to increase the heat transfer area. If an identical heat exchanger is used for both materials, the rate of energy exchange would be highly dependent on the conductivity of the material. The conductivity and specific heat of the two materials for solid and liquid phase is listed in table 5.

Table 5: Material conductivity comparison

Material Conductivity Comparison				
	Erythritol		Magnesium Chloride Hexahydrate	
Property	Solid Phase	Liquid Phase	Solid Phase	Liquid Phase
Conductivity	0.73 W/m.K	0.326 W/m.K	0.704 W/m.K	0.570 W/m.K
Specific heat	1.383 kJ/kg	2.765 kJ/kg	2.25 kJ/kg	2.61 kJ/kg

The specific heat of the material is the amount of energy required to raise the temperature of the material with 1 °C. The rate of thermal

loading and discharge cycles is dependent on both these variables. Evaluating the different materials rate of energy transfer could be done by evaluating the materials thermal diffusivity. The thermal diffusivity of the material represents the ration between the conductivity and the specific heat of the material. Figure 8 shows the thermal diffusivity comparison of the material types.

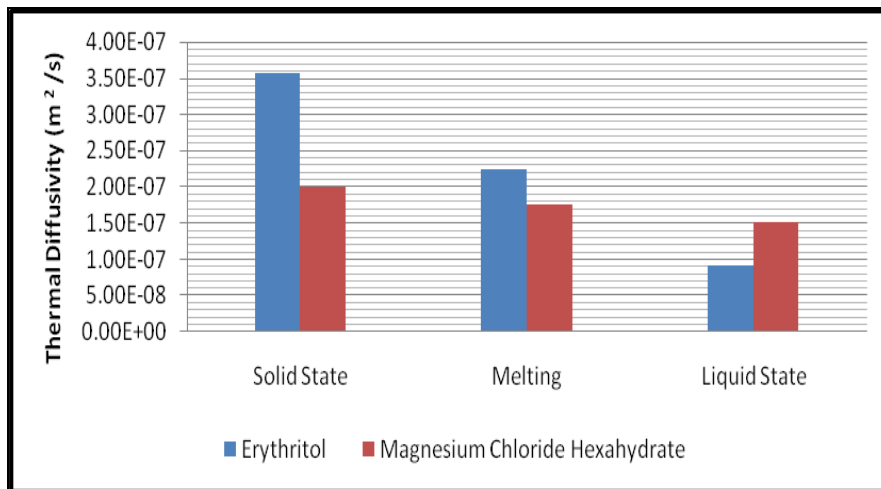


Figure 8: Thermal Diffusivity Comparison

3.4.3. Self Discharge Rate

The rate at which phase change materials loses heat to the surrounding environment during non-operation periods is called the self discharge rate of the material. The self discharge rate of the material enables us to estimate the functional storage period of the latent heat storage system. The self discharge rate of the material is highly dependent on the type of storage unit and insulation material used to encapsulate the PCM and the thermal diffusivity of the material in itself. The use of proper thermal insulation would decrease the tempo of heat dissipation to the surrounding environment by imposing a thermal insulation barrier around the PCM encapsulation. The rate of thermal discharge is calculated and the results are illustrated in figure 9 and 10.

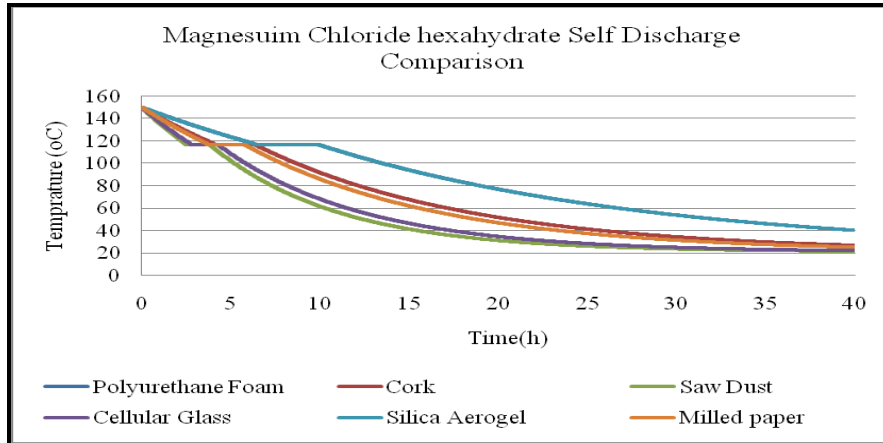


Figure 9: Magnesium chloride hexahydrate self discharge comparison

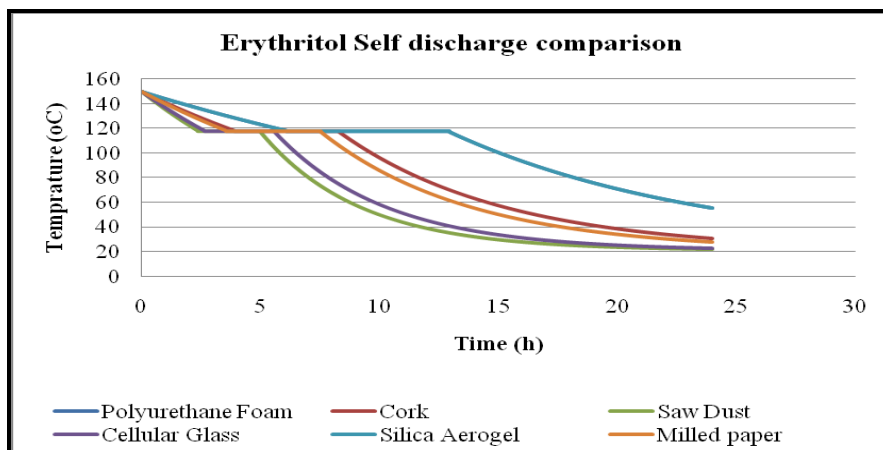


Figure 10: Erythritol self discharge comparison

From figures 9 and 10, magnesium chloride hexahydrate has a lower self discharge rate compared to erythritol. Magnesium chloride hexahydrate may have a lower discharge rate than erythritol but lacks the capability to store large amounts of energy above 100 °C due to its small latent heat. Erythritol discharge rate may be higher but the majority of the energy of erythritol is stored above 100°C and would be more suited for the suggested applications.

4. Conclusion

The challenges faced by sub-Saharan Africa in providing universal access to energy require that all available options must be explored. These options must be sensitive to environmental concerns as well.

In this paper the authors have explored a new energy storage option for sub-Saharan Africa. It has been shown that the use of latent heat energy storage systems has the capability to address small scale residential and industrial sectors of South Africa. The utilization of these types of storage units to store surplus energy could lead to large scale cost and energy savings. This paper focused on selecting the most suited phase change material to be employed in latent heat storage systems for applications with operating temperature ranges between 100°C - 140°C .

This study was able to experimentally prove that erythritol is the most suited material and set the foundation for the development of latent heat systems. The development of an appropriate heat exchanger for each specific application is crucial to the performance of the latent heat storage system.

Further, the use of erythritol in latent heat storage system would yield the most compact and efficient storage but can only be evaluated in depth when a heat exchanger in combination with the phase change material is evaluated as a single unit.

The use of these types of latent heat storage system has the capability to improve current power generation systems, provide sustainable solar cooking products for rural communities and decrease the financial cost involved in industries and residential settings utilising thermal power. The design methodology used in the selection of phase change material may act as a guide for current industries interested in employing these types of storage units. This paper was able to select erythritol as the best suited candidate for latent heat storage systems with operating ranges between 100°C – 140°C .

5. Reference

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