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Development of Capsule for the Encapsulation of High Temperature Phase Change Material and Evaluation of Its Thermal Energy Storage

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Abstract: *Thermal energy storage is an appreciable and cost mitigating solutions to the intermittent power generation by solar, wind and other renewable sources. It bridges the gap that exists between the power supply and its requirement, with a view to ensuring continuous supply of energy. Latent heat thermal energy storage is one of the thermal energy storage systems. It possess high energy density and capable of storing and retrieving energy with change of phase of material. Unappreciable thermal conductivity and leakage forestall the wide use of phase change materials in the desired areas. The aim of this research work was to develop an encapsulated phase change material with a view to protecting the phase change material from external environment, providing increase in heat transfer area and evaluating its heat storage capabilities. So a stainless steel capsule that can encapsulate 30g of phase change material was designed, fabricated and its energy storage capability was evaluated by heating in a furnace and subjecting it to thermal cycles and put in a calorimetric system. The performance evaluation revealed that encapsulated phase change material could store 105.46, 106.77, 107.96, 108.39 and 110.7kJ when heated to or charged with temperatures of 810, 820, 830, 840 and 850^{0}C respectively. The developed encapsulated phase change material finds useful application in solar water heating and concentrated solar power plants where intermittent solar energy supply mitigates their effective operations. It can however act as energy make up for the effective performance of the aforementioned areas of solar energy applications.*

Key words: Capsule, Energy, Phase Change Material, Encapsulated Phase Change Material, Salt, Temperature

INTRODUCTION

Thermal energy storage (TES) is a technology that stocks thermal energy by heating or cooling a storage medium so that the stored energy can be used later for heating and cooling applications and for power generation (Sarbu and Dorca ,2019). Whiffen and Riffat, (2013) stated that thermal energy storage (TES) systems offer attractive properties, enabling economical energy utilization within the built environment. Phase change material (PCM) has become a forerunner in the TES field due to its high-energy storage densities (~10 times that of concrete). According to Salaudeen, (2019) besides the need to generate energy from renewable sources it is very important to store the generated energy. This is hinged on the fact that these sources of energy are not stable; they have intermittent supply as also viewed by Shchukina *et al.*, (2018). For example, solar energy is only available during the day.

It is therefore pertinent to store part of the energy generated during the day; otherwise, it will be wasted. In the same vein, Shchukina *et al.,* (2018) reiterated that phase change materials (PCMs) allow the storage of large amounts of latent heat during phase transition. They have the potential to both increases the efficiency of renewable energies such as solar power through storage of excess energy, which can be used at times of peak demand; and to reduce overall energy demand through passive thermal regulation. Encapsulated phase change materials (EPCM) have a great deal of potential for the storage of thermal energy in a wide range of applications (Solomon, 2013). According to Wang and Zhu, (2018), encapsulation of PCMs is also an effective method for heat transfer improvement in PCMs region. It is to disperse PCMs in Latent heat storage (LHS) unit into groups of small-sized particles closed and surrounded by other materials or the derivatives of PCMs itself after procedure of treatment. So, the direct property of PCMs is actually not changed, and the benefits are mainly contributed to the performance improvement of LHS unit. According to Elmozughi *et al.,* (2014) encapsulation of the PCM has its own challenges such as compatibility between the PCM and capsule materials and the capsule being able to withstand the increase in internal pressure due to the expansion of the PCM during melting.

A lot of work has been carried out on development and performance evaluation of phase change materials and its enscapulation. Notable among these are as stated as follows: Solomon,(2013) developed encapsulated phase change materials capable of storing thermal energy at temperatures above 700°C for use in concentrated solar power (CSP)systems. It was reported that on performance evaluation, there was no reduction in the storage capacity of the sodium chloride EPCMs after repeated thermal cycles. Höhlein *et al.,* (2018) designed PCM storage systems. It was stated that the capsule walls provided a large surface for heat transfer and the thermal resistance is reduced due to the limited thickness of the capsules. Sarbu and Dorca, (2019) developed a two-dimensional heat transfer simulation model of an LHS system using control volume technique to solve the phase change problem. Moreso built a three-dimensional numerical simulation model of an LHS to investigate the quasi-steady state and transient heat transfer in PCMs. Gracia and Gabeza,(2015) reviewed TES in buildings using sensible, latent heat and thermochemical energy storage. They stated that sustainable heating and cooling with TES in buildings can be achieved through Phase Change Materials (PCM) in active systems, Reddy *et al.,* (2014) investigated the effect of PCM capsule material on the performance of TES system during charging and discharging processes. The experimental investigation showed that the charging and recovery of stored energy are less affected by the spherical capsules material. The variables, like charging time and discharging quantity, were varied around 5% for the different capsule materials. Du *et al.,*(2018) provided a state-of-the-art review on phase change materials (PCMs) and their applications for heating, cooling and electricity generation according to their working temperature ranges from (-20^{0}C to +200^{0}C). The review showed that, energy saving of up to 12% can be achieved and a reduction of cooling load of up to 80% can be obtained by PCMs in the low to medium-low temperature range. Khan, (2020) provided an understanding on how to maximize thermal utilization of PCM. This understanding is underpinned by an analysis of PCM Container compatibility and geometrical configuration of the container. Shinde and Suresh, (2014) investigated melting and solidification phenomena of Phase Change Materials (PCM) encapsulated in different capsules. Their findings revealed that melting rate of the solid depends on the shape of the capsule. Generally, elliptical capsules showed higher rate of melting than circular ones. Yi *et al.,* (2015) applied layer-by-layer (LbL) assembly technique to build up ultrathin shells to encapsulate the PCMs. They reported that specifically, using bovine serum albumin BSA as the surfactant, polyelectrolyte encapsulated octadecane spheres in size of ~500 nm were obtained, with good shell integrity, high octadecane content (91.3% by mass), and good thermal stability after cycles of thermal treatments. Alam, (2015) developed an innovative technique to encapsulate PCMs that melted in the 100- 350^{0}C temperature range for industrial and private applications. Finally, a step-by-step trial manufacturing process was proposed to produce large number of spherical capsules. Han *et al.,* (2017) prepared by in situ interfacial polymerization reaction, new microencapsulated phase change material, with organic composite phase change as the core material and polymethylmethacrylate as the shell. The surface morphology of the formed microcapsule was observed by scanning electron microscopy, and its phase change temperature and phase change heat were measured by differential scanning calorimetry. The results of this study showed that the mean diameter is in the range 2–3mm, with a uniform size distribution, and the phase change temperature and enthalpy of microencapsulated phase change material are of 26.2C and 139.68 J/g, respectively.

Su *et al*., (2017) developed a novel microencapsulated phase change material and tested for solar assisted hot water storage systems. They reported that even though the morphology of the sample was affected by the type of emulsifier used for fabrication it recorded the highest energy storage capacity of 126 kJ/kg with encapsulation efficiency of 97.4% as compared with other developed samples. Nomura *et al*., (2015) developed Al-Si alloy microsphere MEPCMs covered by a-Al2O3 shells. They reported that the MEPCM presented a melting point of 5736^{0}C and latent heat of 247 J g and the cycling performance showed good durability. They remarked that these results indicated the possibility of using MEPCM at high temperatures. Elmozughi *et al*., (2014) conducted thermal analysis of high temperature phase change materials (PCM) with the consideration of a 20% void and buoyancy-driven convection in a stainless steel capsule. They reported that the presence of the void has profound effects on the thermal response of the EPCM during both energy storage and retrieval process. Melting and solidification per unit mass of the PCM took longer time when the void was present. Bulk PCMs are not suitable for use without prior encapsulation. Encapsulation in a shell material provides benefits such as protection of the PCM from the external environment and increased specific surface area to improve heat transfer (Shchukina *et al*., 2018). In light of this and to enhance further research work on encapsulation of high temperature phase change material, this research was embarked upon.

MATERIAL AND METHODS

A. *Materials and Equipment*

The material used for the fabrication of the capsule included 1.5mm thick 304 Type stainless steel sheet and the phase change material (PCM) used for encapsulation was sodium chloride (NaCl) salt. The equipment used for fabrication included cutter, welding machine, electrodes, brushes, mallet, scriber, tape rule and weighing scale. An electric furnace and calorimeter with gear oil fabricated by Bakare, (2018) were used for performance evaluation of the encapsulated phase change material.

B. *Design of the Capsule*

A capsule that will encapsulate 30g of the PCM was needed to be designed. 30g was chosen as the pilot mass because it is the larger quantity to be used.

C. *Evaluation of Volume of the Salt to be Encapsulated*

Since the mass and density of the salt (PCM) to be encapsulated are known to be 0.03kg and 1904kg/m^3, then the volume (i.e., the unknown) was deduced using equation (1) that is

$$v = \frac{m}{\rho} \tag{1}$$

where v is the volume of salt to be encapsulated, m is the mass of the salt and ρ is the density of the salt.

$$v = \frac{0.03}{1904} = 0.0000158\ m^3$$

D. *Estimation of the Final volume of the Salt after being Heated to the Desired Temperature*

The expected amount of increase in volume needs to be known so that such an allowance can be created for in the design of the capsule size. Volume expansivity (β) is expressed by Equations (2) as:

$$\beta = \frac{V_2 - V_1}{V_1\ \Delta T} \tag{2}$$

but, $\beta = 3\alpha$, therefore

$$V_2 = 3\alpha\ V_1 (T_2 - T_1) + V_1 \tag{3}$$

Where V_2 = final volume after expansion,

V_1= initial volume before expansion= 0.0000158m^3

ΔT = change in temperature.
T_2 = final temperature = 850^{0}C
T_1 = initial or ambient temperature = 26^{0}C
α = coefficient of linear expansion for the salt= 68.20 × 10^{-6} K^{-1} (Rao *et al*., 2013)
V_2 = 3 × 0.0000682 × 0.0000158(850-26) + 0.0000158
V_2 = 0.0000185m^3

E. Determination of the Radius and Height of the Capsule

Since the capsule is cylindrical in shape, the volume of the capsule is given as
$V = \pi r^2 h$ (4)
Where V is the volume of the capsule, r is the radius of the capsule and h is the height of the capsule and the total surface area of the capsule with both ends closed is given as,
$A = 2\pi rh + 2\pi r^2$ (5)
Where A is the total surface area of the capsule
From Equation 4,
$h = \frac{V}{\pi r^2}$ (6)
Substitute Equation 6 into Equation 5

We have $A = \left(\frac{2V}{r}\right) + 2\pi r^2$ (7)

From Equation 7, the total surface area, A is a function of the radius, r that is

$A = f(r)$ (8)
In order to obtain the minimum and maximum value of the total surface area of the capsule required, Equation 7 was differentiated and equated to zero. That is
$\frac{dA}{dr} = -\frac{2V}{r^2} + 4\pi r = 0$ (9)
Hence $r = (V/2\pi)^{\frac{1}{3}}$ (10)
Put the value of V_2 = 0.0000185m^3 into Equation 10
We have r = 0.014m or 14mm and this is the value of the radius of the capsule where we have turning point.
In order to evaluate whether the total surface area of the capsule is a minimum or maximum Equation 9 was differentiated and the value of r = 0.14m was substituted into the expression
Then $\frac{d^2A}{dr^2} = \frac{0.000074}{r^3} + 4\pi$
Putting the value of $r = 0.014m$
then $\frac{d^2A}{dr^2} = \frac{0.000074}{0.014^3} + 4\pi = 39.53$ (+ve)
Since
$\frac{d^2A}{dr^2}$ is positive, r = 0.014m gives a minimum value of the area of the capsule required
So, the minimum radius of the capsule required = 0.014mm
Therefore the minimum required diameter = 2r = 2 × 14 = 28mm
So the minimum height or depth of the capsule can be obtained from Equation (6)
$h = \frac{V}{\pi r^2}$ (11)
$h = \frac{0.0000183}{\pi \times 0.014^2}$ = 0.030m = 30mm
Therefore, the required capsule that will give allowance for cubic expansion of value $V_2 = 0.0000185m^3$ will have a minimum diameter of 28 mm and height of 30 mm.

However, the selected dimensions for the design of the capsule were 80mm height and 35mm diameter. These are far above the minimum values of the diameter and height determined above. The Orthographic and assembly drawing of stainless steel capsule is shown in Fig.1.

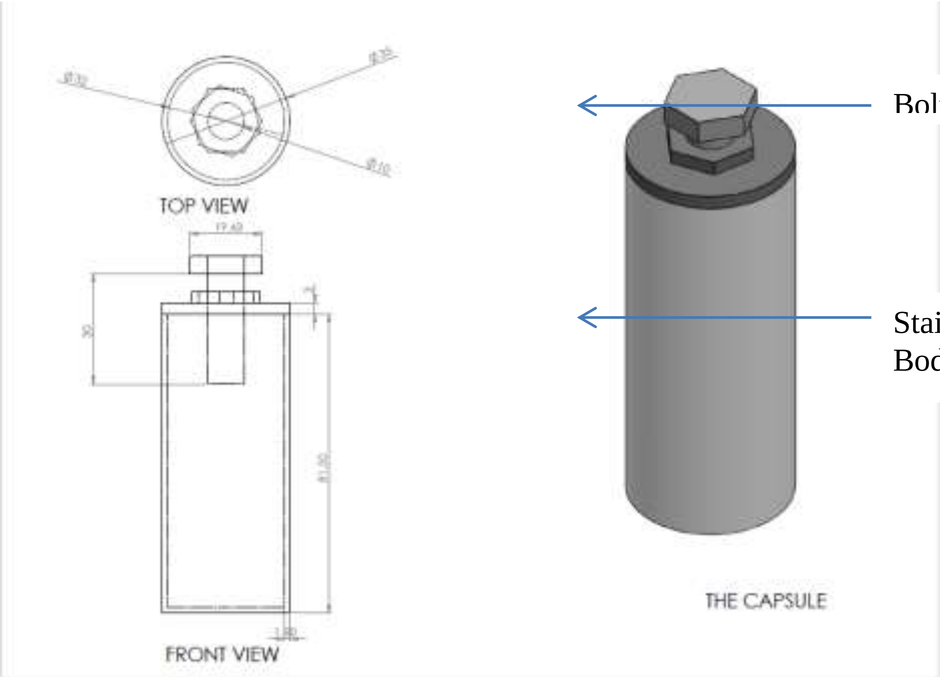

Fig. 1 Orthographic and assembly drawings of stainless steel capsule

F. *Fabrication processes of Encapsulated Phase Change Material (EPCM)*

The dimensions of the capsule are as follows: Diameter =35mm, thickness = 1.5mm and height = 80mm. 30g of the salt were fetched and poured into the capsule and sealed permanently in one end by welding and screw covered in the other end to form the EPCM in line with one of the several ways enumerated by Sarada *et al*., (2013). Six pieces of the capsule were fabricated and the pictorial representation of the capsules is shown in Fig. 2.

Fig. 2: Stainless steel capsule completely fabricated

G. *Performance Evaluation*

The procedure used by Solomon, (2013) was adopted with little modification for the performance evaluation so

(i) The masses of the calorimeter and the gear oil in the calorimeter were measured and recorded. The initial temperatures of the calorimeter and gear oil were measured

(ii) One sample of the EPCMs was weighed and recorded and the initial sample temperature was measured with thermocouple.

(iii) The sample of the EPCM was placed in an electric furnace and heated to 10^oC above the salt's melting temperature based on the recommendation of Solomon, (2013) which stated EPCM should be heated above PCM melting temperature.
(iv) The sample at that temperature was held for over an hour to ensure uniform temperature within it and that all had undergone full phase change
(v) The red hot sample was then evacuated from the furnace and swiftly submerged into the calorimeter. The temperature of the calorimeter displayed by the digital thermocouple on the calorimeter was recorded as the EPCM and calorimeter attained equilibrium temperature.
(vi) The heating process was repeated up to five thermal cycles for the sample with 10^0C increase in the charged temperature for each cycle that is 810, 820, 830, 840 and 850^0C respectively.

H. *Evaluation of the Stored Thermal Energy by Encapsulated Capsule*

Based on the data obtained from the experiment (performance evaluation) and literature, the thermal energy stored by the encapsulated phase change material (NaCl) was determined using the relation stated by Solomon, (2013) as

$$Q_{EPCM,Theo} = m_{cap}\, cp_{cap}\left(T_{s,0} - T_{cal}\right) + m_{PCM} cp_{PCM}{}^{l}\left(T_{s,0} - T_{m}\right) + m_{PCM} LH_{PCM} + m_{PCM}\, cp_{PCM}{}^{s}\left(T_{m} - T_{cal}\right) \quad (12)$$

Where,

$Q_{EPCM,Theo}$ is the theoretical thermal energy stored by the encapsulated phase change material neglecting losses.

m_{cap} = the mass of the stainless steel capsule in kg; cp_{cap} is the heat capacity of the encapsulation material as a function of temperature (J/kg·K); m_{PCM} is the mass of the PCM (kg); $cp_{PCM}{}^{s}$ is the solid heat capacity of the PCM (J/kg·K); $cp_{PCM}{}^{l}$ is the liquid heat capacity of the PCM (J/kg·K); LH_{PCM} is the latent heat of the PCM (J/kg); *Ts* is the sample temperature (K); *Tcal* is the temperature of the calorimeter which was considered to be the same as the temperature of the gear oil in line with Solomon, (2013) in (°C); *Tcal,*0 is the initial calorimeter or gear oil temperature (°C); *Ts,*0 is the initial sample temperature (K); and *Tm* is the melting temperature of the PCM (K) (Zheng *et al* ., 2013) as stated by Solomon,(2013).

RESULTS AND DISCUSSION

The determined parameters of the capsules for encapsulation of the phase change materials viz-a- viz the minimum diameter, minimum height and the volume were 28mm, 30mm and $0.0000158m^3$ respectively. In order to enhance the handling ability of the capsule at an elevated temperature, the selected diameter and height of the capsule of the same volume or capacity of $0.0000158m^3$ that was fabricated were 35mm and 80mm respectively. Based on performance evaluation, the variation of energy stored by the encapsulated sample with their charged temperature is shown in Fig. 3.

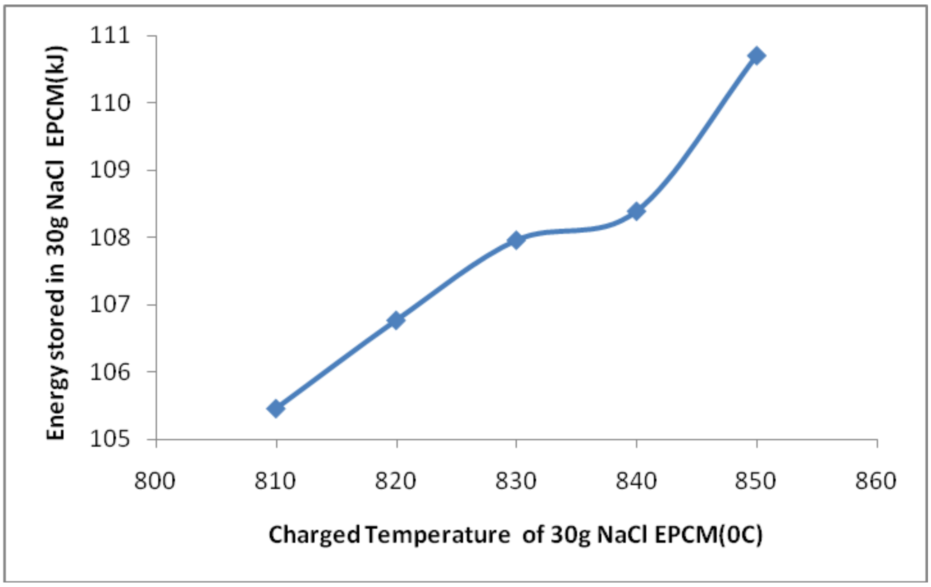

Fig. 3 Variation of energy stored by the encapsulated sample with their charged temperatures

It can be seen from Fig. 3 that the energy stored in the 30g NaCl EPCM increases with increase in the charged temperatures. Maximum energy of 110.7kJ was stored in the EPCM when charged with temperature of 850^0C and minimum energy of 105.46kJ was stored in the EPCM when charged with temperature of 810^0C as evident in figure 3. The trend of variation of 30g NaCl EPCM is similar to the one obtained by Bakare, (2018) who experimented with 30g Na_2CO_3 EPCM.

CONCLUSION

Development and performance evaluation in terms of energy storage of capsule for encapsulation of phase change material has been carried out in this study. Based on the outcome of the study, it can be concluded that the encapsulated 30g phase change material (NaCl) is capable of storing energy which ranges between 105.46 and 110.7KJ when charged with temperature which ranges between 810 and 850^0C. This finds useful application in solar water heating and concentrated solar power plants where intermittent solar energy supplies mitigate their effective operations. It can however act as energy make up for the effective performance of the aforementioned areas of solar energy applications.

RECOMMENDATION

It is recommended that in order to have highly thermal efficient encapsulated phase change material, materials that are slightly or not susceptible to chemical reaction such as ceramics or nickel based alloy should be used to produce capsules for the encapsulation. This should be done in order to prevent corrosion and loss of storage capacity when encapsulated phase change material is subjected to high temperatures for a long period of time.

CONFLICT OF INTEREST

The research work is original and there is no conflict of interest

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