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Development of Encapsulated Shea Butter as Bio-Based Phase change Material for Thermal Storage Application

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***Keywords*— Shea butter, Differential Scanning Calorimetry, Thermal conductivity, Thermal Storage, Computational Fluid Dynamics.**

Abstract *— In this study, unrefined Shea butter is studied as a low-cost biological phase change materials for medium thermal storage applications. The phase change behavior of the Shea butter was investigated using Differential Scanning Calorimetry (DSC). Charging/discharging experiments were carried out to investigate the effect of Heat Transfer Fluid inlet temperature using water (HTF=45°C) with time, in an experimental rig set up consisting of encapsulated Shea butter. A 2-D axisymmetric model was used to model its thermal transient behavior using a Computational Fluid Dynamics (C.F.D) software package. In the DSC results of Shea butter, phase change temperature onset = 31.25°C, end set = 40.2°C, latent heat = 50.34 J/g. Total charging/discharging and melting time of Shea butter was highest at 110/145min at 2 L/min flow rate, and lowest at 70min 6 L/min. However, efficiency was observed to be highest at 68.5% at 6 L/min, and lowest with 63% at 2 L/min. Computational fluid dynamics results are obtained in 2-D temperature-velocity streamlines and 3-D solid-liquid phase change moving boundary of the encapsulated Shea butter with time. These streamlines showed a time dependent heat transfer process during charging of the Shea butter capsules in the experimental rig. The results were used to validate experimental results at an absolute percentage error of 4.7%.*

I. INTRODUCTION

Over the past decades, renewable energy (such as the sun) have gained strong foothold globally. This is due to its clean burning characteristics, sustainable nature, availability and cost effectiveness. Although these energy sources are available in abundance, they are intermittent in nature. Their total availability is dependent on time, weather and geographical location [1]. This limits proper harnessing of these cost effective and reliable energy sources. Thus, energy storage becomes vital in overcoming this challenge [2]. Energy is stored mainly for its utilization at a later time. This helps to level supply-demand patterns, in the savings of expensive fuels, reduces energy waste, improves systems reliability by reducing investments and running costs, leading to a cost effective system [3]. Amongst other energy storage technologies, thermal energy storage (TES) is seen an efficient technology that captures and stores energy in the form of heat [4]. In this way, it is considered one of the most promising technologies that shifts energy loads or reduce peak demand from peak consumption periods to consumption periods [5]. Thermal energy is stored in three main ways; sensible heat, latent heat and thermo-chemical storage [6]. In sensible heat storage, heat is stored by utilizing the specific heat capacity of the storage material and the temperature change [7]. Another way to store thermal energy is through latent heat storage media that are capable of utilizing their high heat of fusion to store energy through phase change [8]. They are generally called Phase change materials (PCMs). These materials have been studied by various researchers in this field over the years [9]. PCMs are basically classified as organic, inorganics and eutectics [10]. They find applications based on their melting temperatures. Thus they are divided into: low temperature PCM range (-20-5°C) which are used in commercial and domestic cooling applications [11], Medium low temperature range (5-40°C) which are used for heating-cooling building applications [12], medium temperature range (40-80°C) for electronics [13], solar hot water heaters [14] as well as solar dryers applications [15], and high temperature range (80-200°C) which are used for waste heat recovery [16], and electricity generation [17]. Paraffins are considered as the most widely used PCMs [18]. Even though they are recyclable, their fossil fuel derived origin makes them nonrenewable, unsustainable, expensive and not environmentally friendly. Inorganic phase change materials on the other hand have lower cost, higher thermal conductivity and latent heat of fusion. However, they are corrosive in nature, lack thermal stability and often undergo phase segregation and separation [19]. Amongst the general requirements of suitable PCMs, an ideal PCM should be biodegradable, sustainable and readily available from a renewable feedstock [20].

Widely studied organic non-paraffinic PCMs include glycols, alcohols, esters and especially fatty acids [21]. These materials are reported to have desirable features for integration in latent heat thermal energy storage systems operating near ambient temperature range at 10-40°C [22].Thus, they can be used for off-grid and renewable energy applications due to their sustainability, non-toxicity, and naturally abundant nature [23]. Long chain saturated fatty acids are naturally occurring PCMs mainly extracted from renewable plants and animal sources [24]. Example include Palmitic acid and Stearic acid which have been studied as PCMs for TES applications in household water heating system [25], are found in palm oil [26] and coconut oil [27] respectively. Hence, raw materials for fatty acids are sustainable, biodegradable, and environmentally friendly.

Several classes of naturally derived materials have been and are currently under investigation to be used as PCM [28]. They provide innovative alternatives to petroleum derived PCM products. This market is expected to witness a Global rise at 19.94% between 2017-2022 forecast periods [29]. Examples of investigated bio-based PCM or blends for thermal storage applications include: Bees wax [30], Olive oil [31], Coconut oil [32], Cocoa butter [33], Soya oil [34], Sugar cane wax [35], Palm oil [36] and Corn oil [37]. These have been reported to have suitable applications in low to medium thermal storage applications.

This study focuses on the use of a low cost bio-based material (unrefined Shea butter) for thermal storage applications. Shea butter is a vegetable fat extracted from the Shea nut of the African Shea tree [38]. Having a fruit bearing lifespan of up to 200 years, Shea tree grows wild across Nigerian forests [38]. It is a triglyceride which composed of 90% saponifiables which are majorly oleic (45%) and Stearic (42%) acids [39]. It is biodegradable, cost effective and locally available. Nigeria produces about 400,000MT of Shea butter annually, making it a top producer of the world Shea butter [40]. However, only a part of this production is utilized in the export market. With major importing companies in Denmark (50,000MT), United Kingdom (50,000MT) and Sweden (25,000), the Shea sector of the Nigerian economy has a large potential to generate wealth and employment for its people [41]. However, this sector is yet to be fully exploited. Even though Shea butter is considered for local consumption, this is only limited to rural households. Most urban settings do not use Shea butter for domestic and commercial cooking as compared to their rural counterparts. Thus, this creates a limited local market for Shea butter. Largely used in the cosmetics industry, it has been studied as a promising renewable feedstock in the production of Bio-diesel [42], in Soap making [43] and as a partial substitute of Cocoa butter in Chocolate industry [44].

II. MATERIALS AND METHODS

Materials used in this work include unrefined Shea butter fat obtained from Minna, Niger State in Nigeria. This serves as the heat storage medium and water is used as the heat transfer fluid.

2.1 Methods

Thermal properties of Shea butter are investigated in this research under the following criteria.

2.1.1. Differential Scanning Calorimetry (DSC)

Differential Scanning Calorimetry (DSC: DSC2 STAR SW 13.00 SYSTEM, METTLER TOLEDO) was used to evaluate the solid-liquid phase change behavior of Shea butter. This procedure [45], [46], [47] was carried out from 23.3°C to 70°C to heat the sample at a rate of 10°C/min.

2.1.2. Thermal conductivity

This was carried out using a thermal conductivity meter. Thermal conductivity of unrefined Shea butter fat was determined at temperatures of solid and liquid phases.

2.1.3 Density

This was measured using a 50ml Density bottle and an analytical weighing balance (Brain weigh B500. SN-11507). Densities above melting point (liquid) and below melting point (solid) were obtained.

2.2. Experimental Rig Set-up

The experimental rig is represented in Fig. 1. It consists of a heat storage tank made of stainless steel with internal diameter of 210.8mm, total height = 508mm and insulated using glass wool. It contains eight layers of Shea butter capsules arranged uniformly supported by a wire mesh. Each layer contains seven PCM capsules uniformly arranged. This gives a total number of 56 capsules. Aluminum was used to encapsulate Shea butter using the shallow container geometry. This, with internal diameter = 68.3mm and thickness = 1.2mm. Passive design was employed to set up the experimental the thermal storage rig. Also the PCM is stationary with moving HTF. The shell and tube container configuration was selected in this study, among other geometry configurations [48]. Temperature indicators were placed at various locations in the Shea butter capsules within the storage tank. This is to measure the temperature of the Shea butter inside the capsules during charging and discharging processes. K-type thermocouples (accuracy +/- 2°C) were placed in the heating/cooling tank to measure the temperature of HTF as charging and discharging proceeds. These were regulated by two temperature controllers (XMTD-239M, operating temp.: 0-399°C). A Flow measuring device was used to measure the flow rate in each experimental run. Flow control valves are located at various inlet and outlet positions to regulate the inflow/outflow of water in and out of the bed. Two centrifugal pumps (P_1-0.2hp, P_2-0.5hp) were used to circulate the HTF during charging/discharging cycles. A backflow was created to return excess HTF to the tank as the pumping pressure was high. The set-up also includes heating/cooling tank which supplies HTF to the PCM tank during both charging and discharging process made up of HDPE. A heater (1000 Watts) is connected to the tank and a temperature regulator which maintains the tank at the desired inlet HTF temperature in each experimental run.

2.3. Experimental Run

To investigate the thermal storage capacity of the encapsulated Shea butter, charging/discharging cycles were carried out under the experimental rig set up. This experimental flow facility is represented in Fig. 1. Experimental processes were carried out at HTF inlet temperatures of 45°C and flow rates of 2, 4 and 6 lit/min. During the charging process, heated HTF from tank H_1 is circulated using pumps P_1 and P_2. Initially, all valves are closed with the exception of V_2. HTF is circulated through this valve to and from H_1. This is to ensure proper mixing of the HTF, thus ensuring a uniform temperature of the HTF in tank H_1. Once this temperature is attained (indicated by T_2), valve V_1 is opened to allow the flow of HTF to the PCM tank at a specified volumetric flow rate. This flow rate is measured using the flow meter, F_1. Valve V_3 is kept closed until the thermal tank is filled up and the Shea butter capsules are completely immersed in the HTF. The level is monitored using the level indicator, L_1. Once the tank is filled, V_3 is opened and adjusted to maintain a uniform inflow and outflow of the HTF. Temperatures of the PCM and the tank HTF are been monitored and recorded at various time intervals. HTF leaving the thermal tank is collected at H_3 and then circulated back to tank H_1. Charging experiments are stopped when the Shea butter temperatures and HTF temperature are in equilibrium. This procedure is repeated at flow rates of 4 L/min and 6 L/min. During the discharging process, the same procedure is repeated. However, the HTF temperature is used at ambient temperature.

The efficiency of the thermal storage system is defined as,

$$\eta = \frac{Q_d}{Q_c} \qquad (1)$$

$$Q_c = (mC_p\Delta T)_f + (mC_p\Delta T)_{lpcm} + (mL)_{pcm} + (mC_p\Delta T)_{spcm} \qquad (2)$$

$$Q_d = (mC_p\Delta T)_f + (mL)_{pcm} + (mC_p\Delta T)_{spcm} \qquad (3)$$

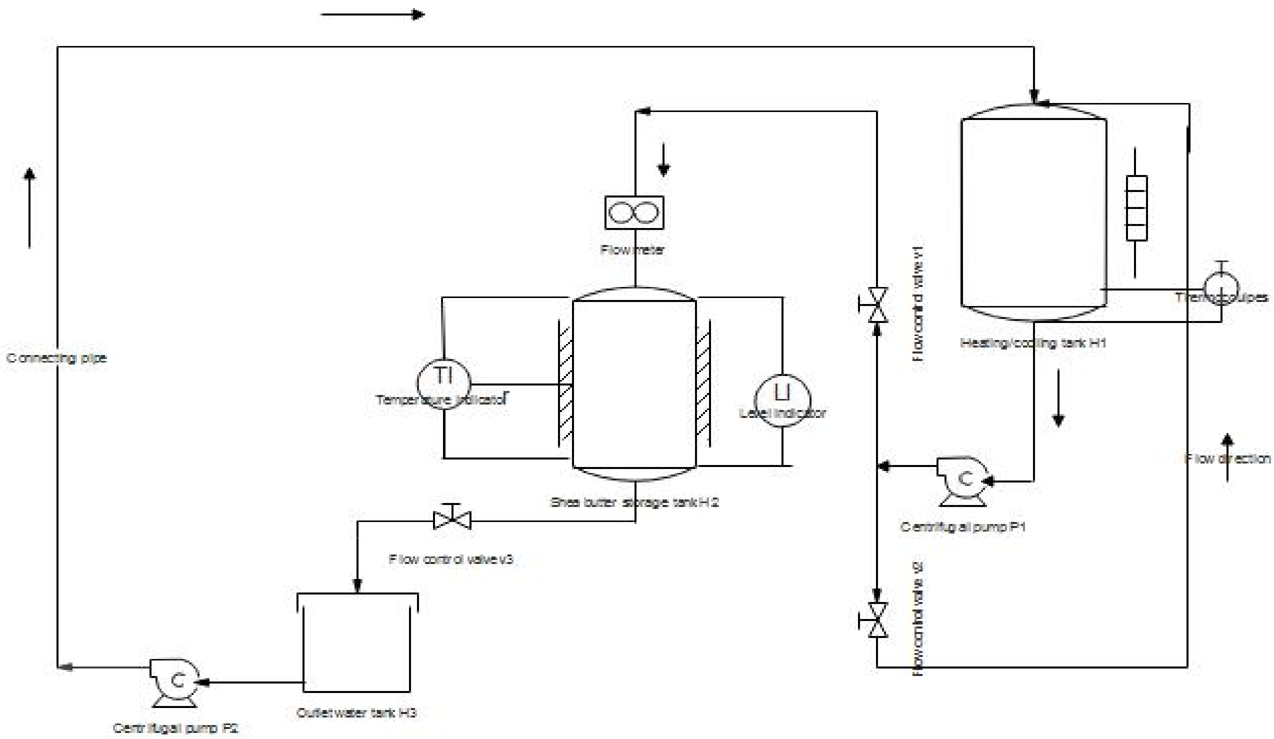


Fig.1: Experimental flow facility

2.4. Computational Analysis

The numerical modeling of the Shea butter storage unit was carried out using COMSOL Multiphysics V5.5. This software provides an interactive environment for modeling and simulating designs in various engineering fields. Assumptions made in this modeling are:

i. Incompressible fluid (HTF)
ii. Constant density and thermophysical properties of Shea butter.
iii. HTF is isotropic.
iv. Convection inside the capsule is negligible. Thus, Shea butter is treated as a solid/immobile liquid.

The study is carried out using a 2-D axisymmetric model. The flow is considered to be fully developed non-isothermal laminar flow.

III. RESULTS AND DISCUSSION

DSC analysis of selected PCMDSC thermogram of the investigated Shea butter fat is represented in Fig. 2.

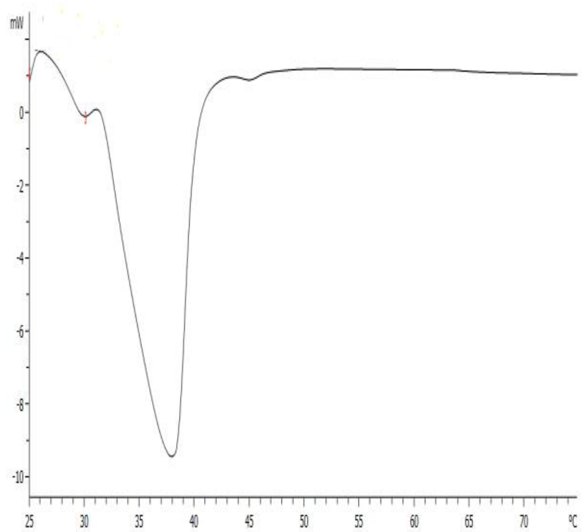


Fig.2: DSC thermogram of Shea butter

It is observed that Shea butter was observed to exhibits the general phase change behavior of organic phase change materials [44]. From the graph, two dips exist: the first is the solid-solid phase transition of Shea butter, and the second is the melt range transition. The solid-solid phase transition occurs between 28°C and 31°C. The melt range which is known as the ``mushy zone'' during which the Shea butter first softens and then melts. Here, the mushy zone begins to dip around 32.5°C and peaks at the peak melt point (T_m) of 37.5°C and ends at 40.2°C.Latent heat (ΔH) at 50.36 J/g. A summary of the Shea butter characterization results are presented in Table 1.

Table 1: Characterization results of Shea butter

Property	Value
Melting Onset (T_o)	32.5°C
Melting Peak Temperature (T_m)	37.5°C
Melting Endset Temperature	40.2°C
Latent Heat	50.34 kJ/kg
Percentage Purity	99.4 %
Molecular Weight	194.20 g/mol
Density Solid	$910 kg/m^3$
Thermal Diffusivity (Solid)	0.101 mm^2/s
Thermal Diffusivity (Liquid)	0.118 mm^2/s
Density Liquid	880kg/m^3
Thermal Conductivity Solid	0.11W/m.K
Thermal Conductivity Liquid	0.26W/m.K

3.2 Temperature-Time Variation for Charging/Discharging cycles

Figure 4.5 and 4.6 shows the variation of temperature with time of the Shea butter during charging and discharging cycles respectively. A reduction in the time was observed with increasing HTF flow rate. Thus, charging at 2, 4 and 6 L/min =110, 100 and 70min respectively, which gives a charging improvement at approximately 16% and 15% with increase in flow rate. During discharging, the time was observed from 145, to 115 to 95 min at 2, 4, and 6 L/min. This effect in reduction gave a time improvement of 20% and 17%. The charging process require less time than discharging because the melting process is convection dominated. However, during discharging, the heat transfer rate between the capsule and the HTF is low as it forms a high resistance solid layer inside the shell of the capsule [45]. Thus, discharging is a solidification dominated process, which is slower. The efficiency of the experimental rig set up was obtained at 63%, 63.5% and 68.5% at 2, 4 and 6 L/min respectively. This is shown in Fig. 3 and 4.

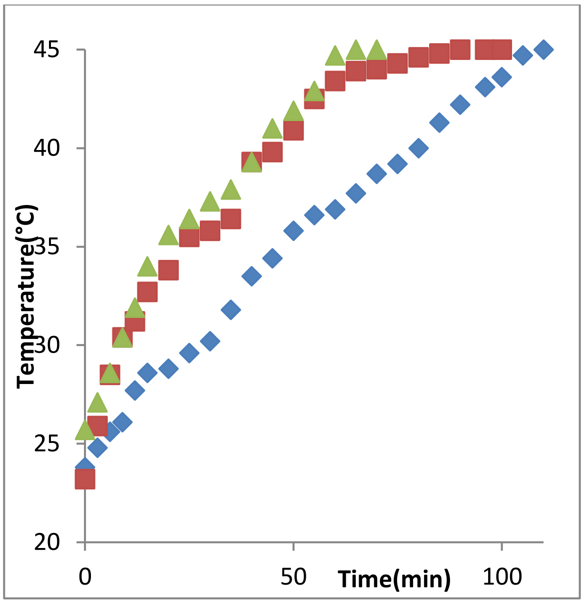


Fig.3: Variation of Temperature with time during charging of encapsulated Shea butter.

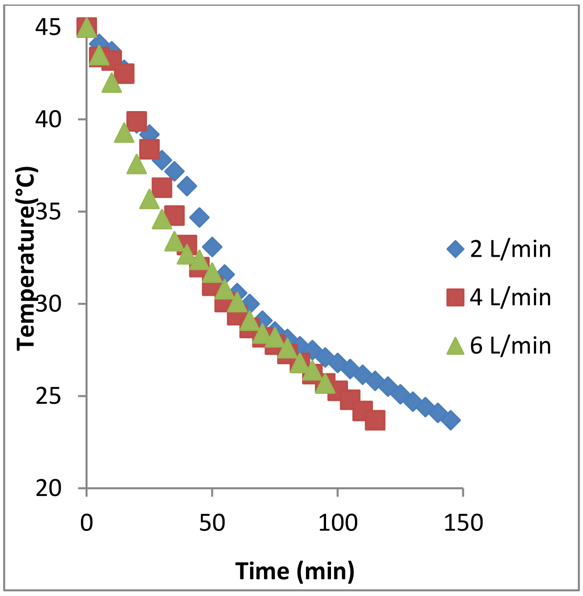
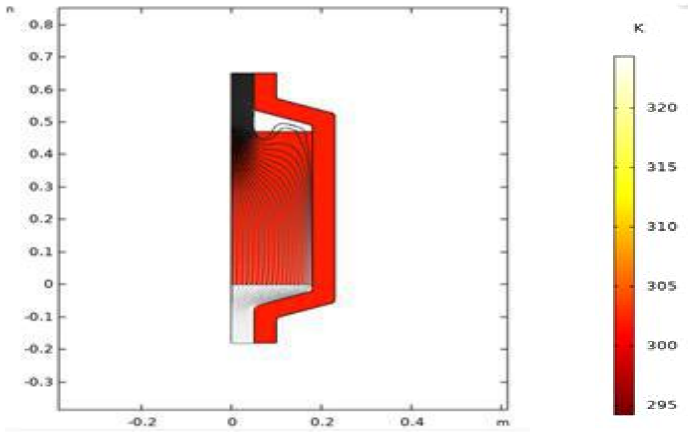


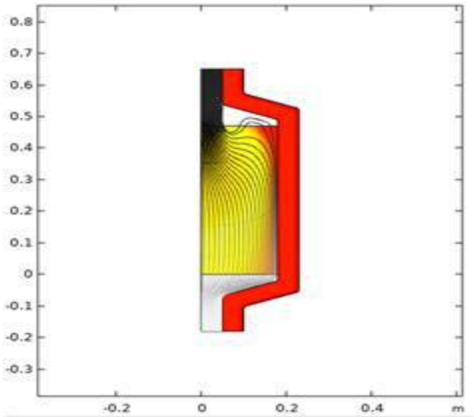
Fig.4: Variation of Temperature with time during discharging of encapsulated Shea butter.

3.3. Results of computational analysis

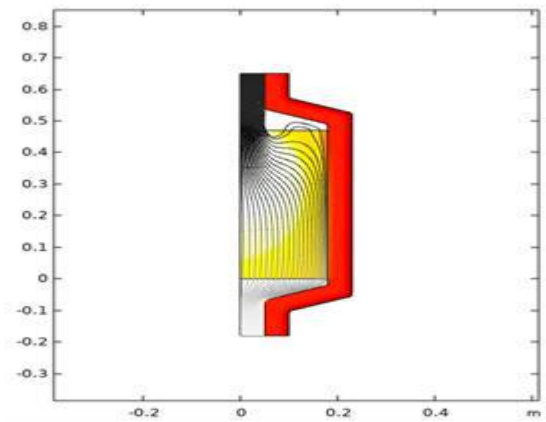
Figure 4 presents the result of the temperature-velocity streamlines for the heat transfer process in the thermal storage tank. The results show the temperature variation during the charging process in the experimental rig with time. The temperature field is colored, while the velocity streamlines are in grey. Before the beginning of the charging process plate (a), the encapsulated Shea butter is at ambient with the surrounding temperature with no heat transfer. As the HTF is circulated, charging proceeds and heat is transferred by convection (b). Temperature in the storage tank rises with a radial heat transfer from the center of the tank towards the end of the walls (c) at 30min charging. Temperature in the storage tank reaches the HTF inlet temperature after about 105min. Thus, the system is considered to be fully charged (d)



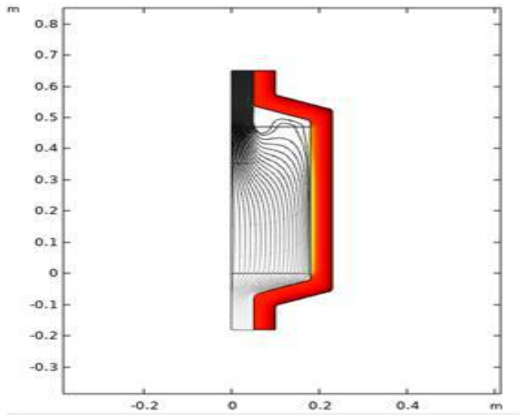
a. At 0min charging



b. At 15min charging



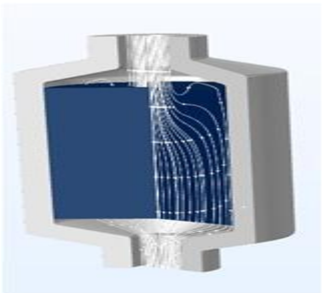
c. At 30min charging



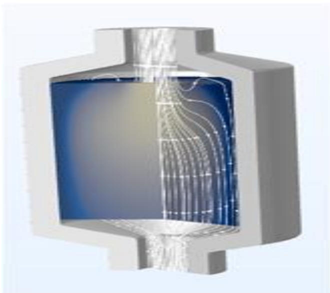
d. At 105min charging

Fig.4: Temperature-velocity streamlines of the thermal storage tank during charging process.

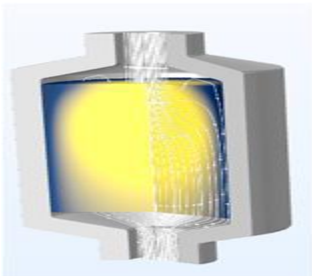
The evolution of the melting process of encapsulated Shea butter is visualized in figure 5 (a-e). This process illustrates the temperature contour along the bed at various time steps as charging of the Shea butter proceeds. The solid phase distribution is represented in blue, while the liquid phase distribution in yellow. The level indicator (0-1) shows how much level of the Shea butter is converted to liquid. Here, 0 stands for solid state and 1 for liquid state. Any value within this range is considered to be in a mixed phase state. At the beginning of the charging process (0min), Shea butter is in a completely solid state.



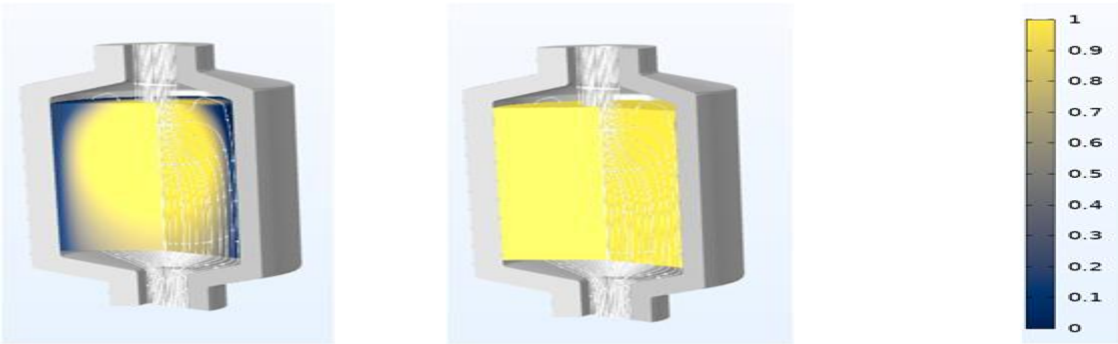
a. 0min



b. 15min



c. 30min



d. 90min e. 105min

Fig.5: Solid-liquid phase change process of encapsulated Shea butter at various time intervals during charging.

IV. CONCLUSION

I. Thermal characterization results of Shea butter using DSC revealed an on set solid-liquid phase change temperature at 31.25°C, peak at 37.75°C, endset at 40.2°C with a latent heat of melting of 50.36 J/g. Specific heat capacities of Solid and Liquid phases of 1.2 kJ/kg and 2.5 kJ/kg respectively. Thermal conductivity was observed to increase linearly from 0.11-0.26 W/m.K at 15-35°C. Density of solid at 910 kg/m^3, liquid at 880kg/m^3 respectively.

II. Successful assembly of an experimental rig capable of storing 7.53kg of encapsulated Shea butter in 0.671mm internal diameter capsules utilizing water as a HTF fluid using both sensible and latent heat approach.

III. Performance studies on the encapsulated Shea butter under charging and discharging cycles at flow rates of 2, 4 , 6 L/min showed a decrease in charging, melting and discharging time of the encapsulated Shea butter with increase in flow rates. However, the efficiency of the system increased from 63% to 68.5% when the flow rate was increased from 2-6 L/min.

IV. Computational analysis results showed a dynamic response of the temperature and solid-liquid phase change behavior of the encapsulated Shea butter during charging. The resulting charging and melting time of encapsulated Shea butter validated the experimental results at an absolute percentage error of 4.7%.

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