Impact of Void Spaces Due to Phase Change Material Based ThermalEnergy Storage System

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Abstract

This study is conducted to examine the effects of void spaces of air in phase change material based system of thermal energy storage (PCM-TES). A thermal simulation and analysis on a 2d axis symmetrical model are performed to simulate the effect of phase change, buoyancy driven convection and heat transfer. Two models are compared, one with a 20% air space and the other without. Both models are steady in PCM volume. Results obtained from the simulation are validated by experimental results. The significant volume taken up by the void space could be reduced and replaced with more phase change material (PCM); which will increase the heat storage capacity of the system. Hence, understanding the effects of void spaces will be paramount in the development of future PCM-TES system designs.

Keywords: phase change material; latent energy storage; thermal energy storage system; macro-encapsulation; thermal simulation; void space

1. Introduction

In the recent decades, the need to source for and develop renewable energy sources have been an increasing concern. Replacing traditional and environmentally unfriendly methods with solar energy is not novel but there are many ways to further improve its systems. There are two main methods of conversion of solar energy into electrical energy, namely the use of photovoltaic (PV) cells or concentrating solar power (CSP) plant [1, 2]. PV cells utilize semiconductors and directly convert solar energy into an electrical output [3]. Meanwhile, CSP plants use mirrors to concentrate the solar rays to thermal energy, and using the stored thermal energy to drive power generation cycles such as steam engines. The benefit of a CSP method over the PV method is the ability to produce electricity in the absence of sun irradiance [4]. This conversion of solar energy into thermal energy is made possible by the use of thermal energy storage (TES) systems [1, 2].

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Phase change material based thermal energy storage (PCM-TES) system embodies sensible and latent heat storage method as its primary working principle. It has many practical applications in the urban clean and green cities such as in concentrated solar power plants, waste heat thermal storage systems and even in building materials.

PCM based TES systems usually consist of a PCM macro-encapsulated within a thermally conductive enclosure, with or without a thermal enhancing component such a metal lattice structure to improve the overall thermal conductivity of the system. The containing vessel is often considered as a pressure vessel and takes on multiple stresses [5], depending on the method in which it was filled. The PCM will typically fill up about 80% of the enclosure's volume [6, 7] while a void space remains to accommodate for the thermal expansion of the PCM during its phase transition from solid state to liquid state [6, 7]. A method used to work around this problem is to encapsulate the PCM while in its expanded liquid form [8]. This method causes a vacuum to form during solidification which forms a negative pressure.

However, the void space is absolutely necessary within the current design of the PCM-TES system [9-13], but the space of air creates a layer of insulation which adversely affects the overall thermal conductivity of the system [6]. In theory, the rate of heat transfer will be hindered by the reduction in contact surface area and the blanket of air.

This study explores numerically and experimentally the effect of the air void space on the heat transfer within a cylindrical enclosure. The comparison study comprises of two models, one with a standard 20% air void space and the other without; both models with equal volumes of PCM. In this paper, the numerical simulation and CAD drawing will all be conducted via finite element analysis, solver and simulation software, COMSOL Multiphysics and SOLIDWORKS respectively. An experiment with the physical PCM-TES model will be carried out under similar circumstances to obtain the actual surface temperature data. Verification of the simulated results is performed by comparing the simulated results with the experimental results.

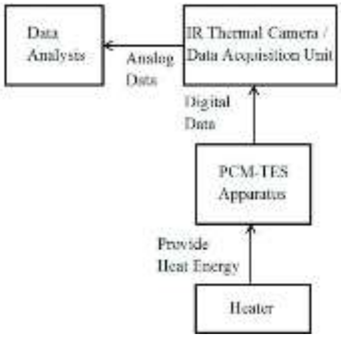

Figure 1: Proposed Experiment Workflow

The figure above shows the proposed workflow for the experiment that consists of the equipment required and the flow of data. The apparatus will be heated up via an electronic heating bed and temperature captured by an IR thermal camera [14].

The simulation and experimental results demonstrated a good agreement that the void space has an adverse and undesirable effect on the overall heat transfer in a phase change material based system. Therefore, the obtained results could be beneficial and valuable to the future design of PCM based TES systems as well as other encapsulated PCM based system.

Nomenclature

C_P	Specific Heat Capacity (J/kgK)	*Greek symbols*	
$\boldsymbol{F}$	Volume Force Field (N/m^3)	α	Phase Volume Fraction
H_f	Heat Storage Capacity (J/kg)	Δ	Difference
k	Thermal conductivity (W/mK)	θ	Phase Mass Fraction
p	Pressure (Pa)	μ	Dynamic Viscosity (kg/m s)
q	Heat Power (W)	ρ	Density (kg/m^3)
s	Seconds		
t	Time (s)		
T	Temperature (or K)		
$\boldsymbol{u}$	Velocity Field (m/s)		
Q	Heat Source (W/m^3)		

1.1. PCM-TES System Information

The PCM-TES system is made out of a two circular aluminum bodies which encapsulates the phase change material (PCM) and the air void space. The system houses a commercially available PCM, RT35HC by RUBITHERM® Technologies GmbH, which has a melting point of 35 over a temperature range of 3 . The system also has a vent valve to prevent over-pressuring

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during the encapsulation process, after all, the system is largely considered as a pressure vessel whose dimension is Ø100 x H 20.5 mm.

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Figure 2 shows the CAD drawings of the PCM-TES, with and without the air void space. The two models are similar to one another, except for the void space. The PCM-TES was designed using CAD software, fabricated out of 6061 aluminium and assembled for testing.

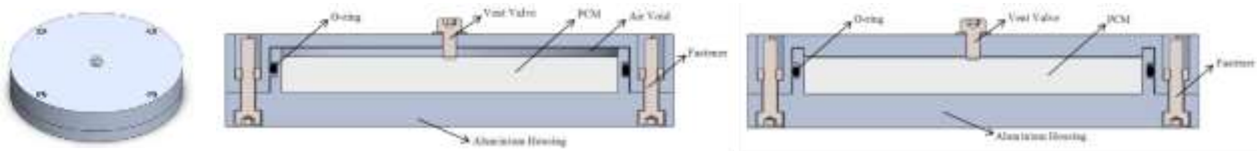

Figure 2: Isometric and Sectional View of the PCM-TES, with and without air void

The PCM-TES comprises of aluminium housing with a storage space for the PCM and is securely encapsulated and fastened by corresponding socket bolts and nuts. For comparison sake, one enclosure is fully filled and filled via the vacuum method; while the other is 80% filled with PCM and a 20% allowance air gap for thermal expansion of the PCM.

Figure 3: Isometric and Exploded View of the PCM-TES

In Figure 3, the fabricated PCM-TES system is shown. The physical item is identical to what was shown in Figure 2.

2. Simulation Setup

An analysis of the effects of void spaces on the heat transfer within a PCM-TES is conducted by modeling the phase change within the enclosure and measuring the temperature on the top surface. Hence, a comparison study via numerical simulation with COMSOL is done to understand the adverse effects this layer of air solution has on the overall heat transfer of the PCM-TES.

To reduce computational cost, the PCM-TES model has been simplified and PCM assumed to be a pure substance. The Navier-Stokes equations have been used to model the buoyancy-driven convection in the liquid phases, air and melted PCM. The apparent heat capacity method is used to model and track the location of the solid/liquid interface during phase change.

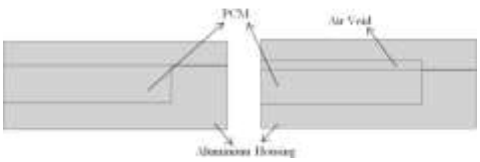

Figure 4: 2D Model in COMSOL

Due to the rotational geometry of the PCM-TES, the simulation was performed on a 2D axisymmetric geometry shown in Figure 4; which depicts the PCM-TES without the air void (left) and with the air void (right).

2.1. Boundary Conditions

The main boundary conditions for the study are as follows:

- Physics used is the heat transfer in solid, liquid and phase change material
- Time dependent
- Simulation time of 4100 seconds, with step size of 5 seconds
- Initial temperature of 298K (25)
- Initial pressure of 1 bar
- Heat source is a constant 323K (50)
- Gravity effect

The material properties used in the simulation is shown in Table 1.

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Table 1: Table of Material Properties

Material	Phase	Thermal Conductivity, k [W/mK]	Heat Capacity, C_P [J/kgK]	Heat Storage Capacity, H_f [kJ/kg]	Density, ρ [kg/m^3]
PCM (RT35HC)	Solid/Liquid	0.2	2000	240	880/770
Air	Liquid	Defined by piecewise functions, dependent on temperature			
Aluminium	Solid	167	896	-	2700

3. Experiment Setup

The results obtained from the experiment were used as verification of the accuracy in the simulation carried out. The experimental setup consists of the PCM-TES (shown in Figure 3), thermocouples, infrared thermal camera, a heating bed, a data acquisition unit and a laptop computer. The physical experiment rig, sequence and layout are depicted in Figure 5.

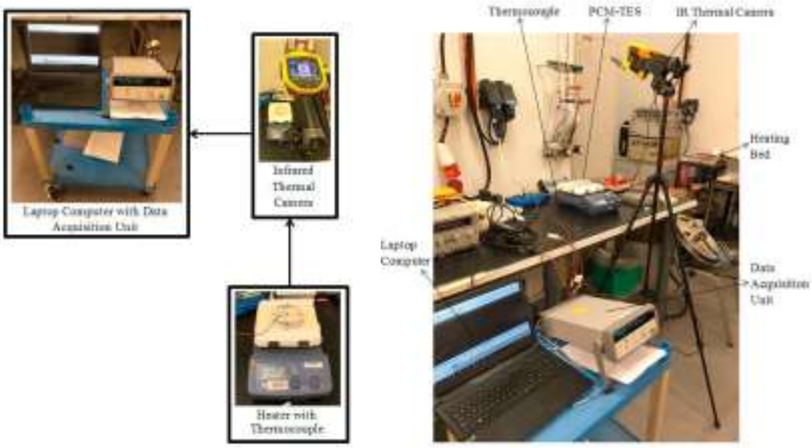


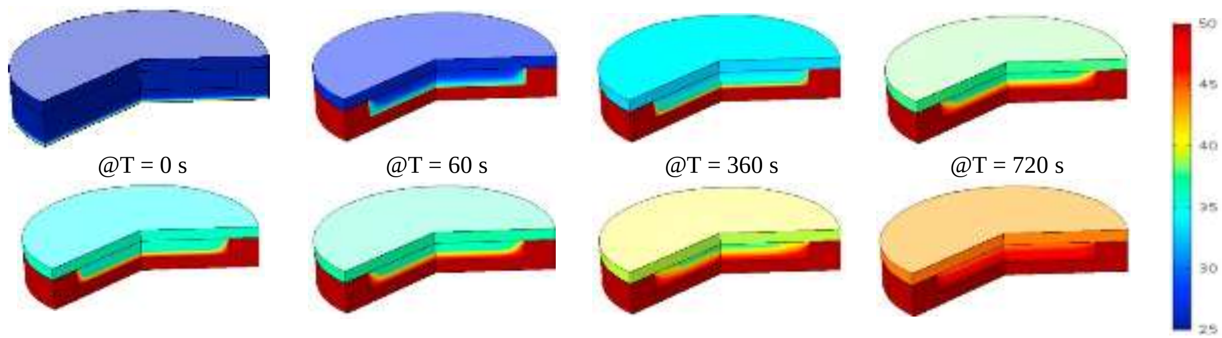
Figure 5: Experimental Setup, Sequence (left), Layout (right)

The heating bed provides a steady 50 temperature to the PCM-TES for 4100 seconds. The thermocouple is attached to the PCM-TES top surface aluminium cover. Whereas the IR thermal camera is focused directly on the top surface of the PCM-TES, which is covered with masking tape that has a known emissivity value of 0.92. The data from the thermocouple and IR thermal camera are automatically captured with 5 seconds interval by the data acquisition unit and data-logging software. The data are later further analysed and processed via computer software.

4. Results and Discussion

4.1. Simulation Results (Without Void Space)

The objective of the simulation is to provide an inkling of the phase change process within the opaque aluminum enclosure as well as demonstrating the heat transfer through the PCM-TES to its surface.



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@T = 1440 s @T = 2160 s @T = 2880 s @T = 4100 s

Figure 6: 3D Simulation Results, without Void Space (Temperature)

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As depicted in Figure 6, the 2D COMSOL model has been axially rotated and forms a 3D model similar to that of the physical PCM-TES model. Figure 6 also shows the temperature rise of the PCM-TES without a void space. From T = 720s to T = 2880 s, the PCM in the core only experiences a slight temperature rise.

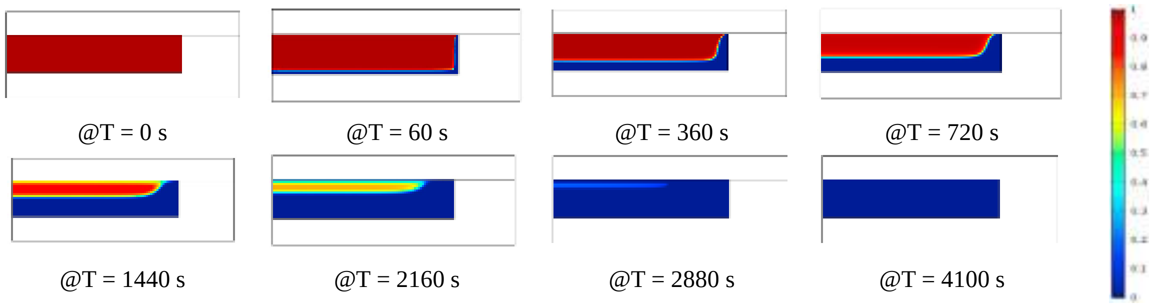

Figure 7: 2D Simulation Results, without Void Space (Phase Ratio)

Seen in Figure 7 is the PCM within the PCM-TES without void space. Due to heat transfer from the heat source, which is at the base, the PCM melts from the base and spreads up wards. The top cover is also heated in the process and the top of the PCM layer also experiences a temperature gradient and starts to melt between T = 1440s to T = 2880s. The PCM is fully melted at T = 3000s, where –1‖ refers to the PCM in full solid state and –0‖ refers to the PCM in full liquid state.

4.2. Simulation Results (With Void Space)

A simulation studies was carried out on the PCM-TES model with air void space. The simulation provides an inkling of the developments within the model which is unachievable with the opaque PCM-TES system.

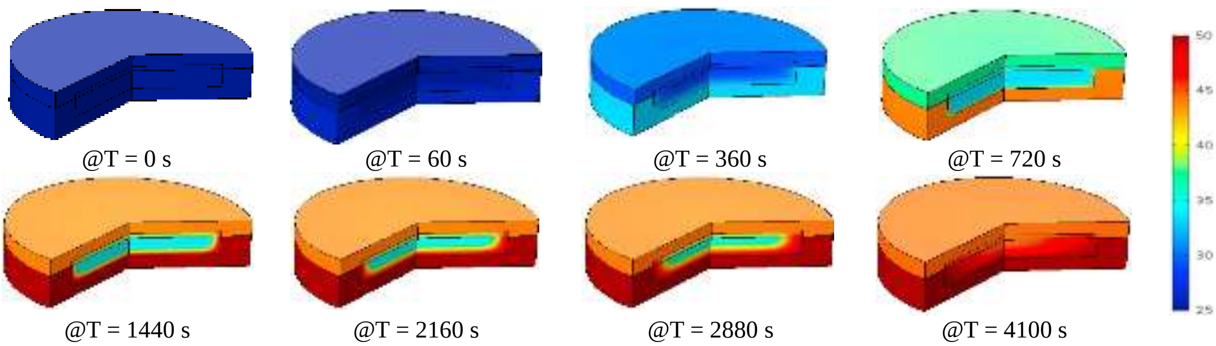

Figure 8: 3D Simulation Results, with Void Space (Temperature)

As depicted in Figure 8, the 2D COMSOL model has been axially rotated and forms a 3D model similar to that of the physical PCM-TES model. Figure 8 also shows the temperature rise of the PCM-TES with a void space. From T = 720s to T = 2880 s, the PCM in the core only experiences a slight temperature while the enclosure experienced an almost linear temperature rise.

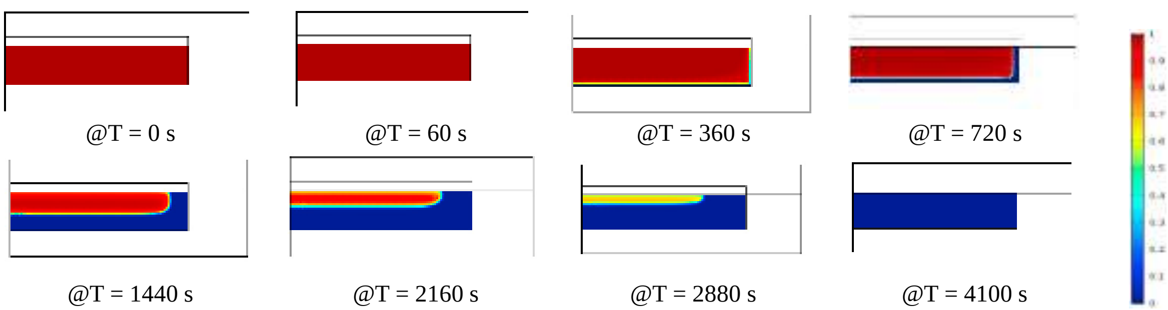

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Figure 9: 2D Simulation Results, with Void Space (Phase Ratio)

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The PCM phase ratio within the PCM-TES with void space is shown in Figure 9. Due to heat transfer from the heat source, which is at the base, the PCM melts from the base and spreads upwards. The top cover is also heated in the process and the top of the PCM layer also experiences a temperature gradient. However, due to the presence of the air void space, the heated cover is unable to transfer that energy to the PCM. The PCM is fully melted at 3600s, where –1‖ refers to the PCM in full solid state and –0‖ refers to the PCM in full liquid state.

4.3. Experimental Results

The objective of performing the experiment is to verify and ensure that the results obtained in the simulation is accurate and agrees sufficiently with the experimental results. The experiment possesses many unaccounted natural phenomena which are extremely difficult to simulate. Therefore, it is expected to have a slight difference from the simulation results.

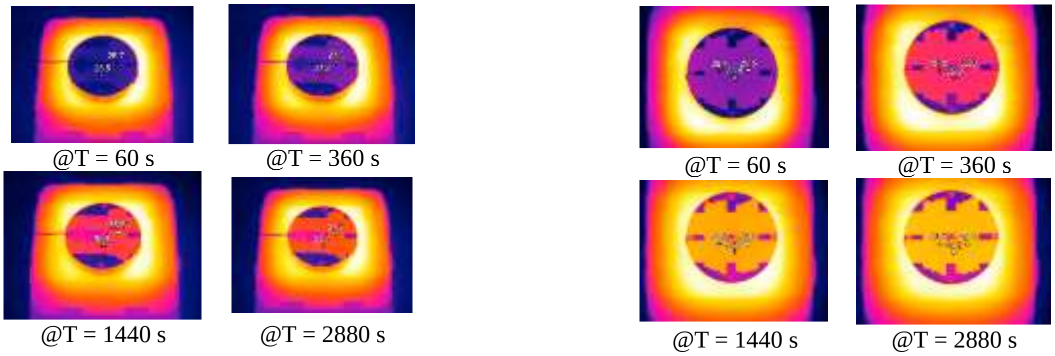
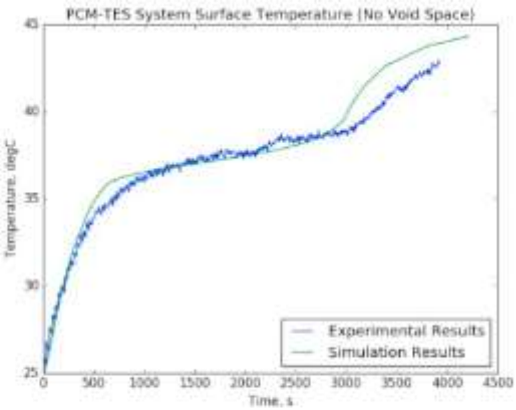


Figure 10: Experimental Results, without Void Space (left), with Void Space (Right)

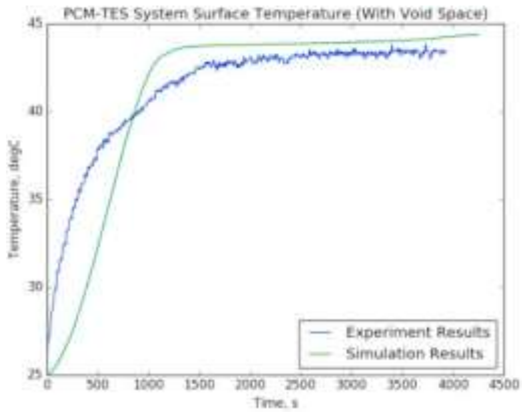
Figure 10 depicts the infrared thermal images captured by the thermal camera for the PCM-TES with and without the 20% air void space. As seen by the temperature increment, it rises much faster than the PCM-TES without the air void space and peaks out in a shorter time too.

4.4. Comparison of Results

The results obtained from the simulation are cross compared to those obtained from the experiment. It is observed that the results agree with one another as demonstrated in Figure 11.



Without Void Space



With Void Space

Figure 11: Comparison Graphs

As seen in Figure 11, the PCM-TES with 20% air void space does not portray the typical latent storage characteristics where temperature does not rise due to the phase change process. Unlike the PCM-TES without the void space, the temperature rises similarly to a sensible heat storage system. The PCM in the PCM-TES with the air void space also took 600 seconds longer to fully melt. This is due to the lack of contact surface area between the PCM and top cover of the PCM-TES system which leads to a reduction of effective latent heat absorption and hence, reducing its overall effectiveness as a latent heat storage system.

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5. Conclusions

The heat transfer analysis of the effect of void space in the macro-encapsulated PCM-TES system was conducted based on a 20% void space on the top of the layer of PCM. The results obtained from the simulation clearly agree with that of the experiment and they both demonstrate the adverse effect of the void space. The PCM-TES with the void space behaves against the natural characteristics of the phase change material. This is mainly due to the lack of direct surface-to-surface contact between the PCM and the aluminium housing. The void also acts as a layer of insulation between the PCM and the housing.

These results places greater emphasize on the importance of eliminating the void space in such macro-encapsulated PCM-TES systems, hence increasing the overall efficiency and effectiveness of the system. The conclusions from this study can be further used to aid and change the design of typical macro-encapsulated PCM-TES systems.

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