

# Development of a Portable Solar Room Heater Using Phase Change Material (PCM)

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**Abstract:** The traditional method of warming rooms at night during harmattan in Northern Nigeria is either dangerous or inadequate. An alternative method of room warming is south. Four prototypes of solar room heaters were developed using glycerine as the Phase Change Material and stainless steel as the heat transfer medium. The dimensions of the prototypes solar room heaters were Type A (diameter = 15.2 cm, length = 30.4 cm), Type B (diameter = 15.0 cm, length = 26.0 cm), Type C (diameter = 15.0 cm, length = 22.0 cm) and Type D (diameter = 16.0 cm, length = 22.0 cm). The average charging period for the solar room heaters was Type A (1 hour 40 minutes), Type B (1 hour 30 minutes), Type C (1 hour 40 minutes) and Type D (1 hour 20 minutes). The average discharging period for the solar room heater was approximately 25,000 seconds (6 hr 57 min). The duration for the charging and the discharging of the room heater has a positive linear relationship with the volume of the phase change material.

**Keywords:** Thermal energy, Phase change material, latent heat, room heater, glycerine

## I. INTRODUCTION

The ambient temperature during the Harmattan season in Northern Nigeria is very severe, sometimes as low as single digits at the night. Many families adopt one form of room warming or the other. Electric room heating device/ appliance provides the needed warmth to the rooms during the cold weather. However, the epileptic electricity supply is a major setback. The alternative heating using charcoal is hazardous. Charcoal uses oxygen in combustion (producing carbon dioxide) before it could release the heat and when oxygen is depleted the oxidation reaction is incomplete leading to the production of carbon monoxide, this has led to many cases of carbon monoxide poisoning<sup>[1]</sup>. Carbon monoxide has been known to be toxic as it has a very high affinity to haemoglobin, 400 times higher than oxygen<sup>[2]</sup>. There is therefore the need to develop an alternative room heater with zero emission of carbon monoxide and with a capacity to discharge heat over five hours at the night.

Thermal Energy Storage (TES) has become one of the most pressing topics worldwide. The serious concern of the public regarding greenhouse gases emissions, limited reserves of fossil fuel, and rapid growth of global energy has shed the light on the effective utilization of thermal energy<sup>[3]</sup>. Thermal energy storage provides a key method to reduce energy consumption and dependency on fossil fuels<sup>[4]</sup>. Efficient utilization of energy can be achieved by matching the energy supply with demand by utilizing thermal energy storage systems<sup>[5]</sup>. In this paper, a solar room heater was developed using Phase Change Material (PCM) as a medium of heat storage encapsulated in a stainless-steel container that allows fast charging of heat during the day and slow heat release during the night.

### A. Thermal Energy Storage

Thermal energy storage (TES) is a technology that stores thermal energy by heating or cooling a storage medium so that the stored energy can be used at a later time for heating or cooling applications and power generation<sup>[6]</sup>. Thermal energy storage (TES) systems can be broadly categorized into three types: the sensible heat storage (SHS) system, the latent heat storage (LHS) system and the thermo-chemical energy storage system<sup>[7]</sup>. In the SHS system, energy is stored by raising the temperature of the storage material. There is no phase change during the heating or cooling of the storage material. The amount of sensible heat stored is given by equation 1<sup>[8]</sup>, where  $Q$  is the sensible heat stored,  $m$  is the mass of storage material,  $T_1$  and  $T_2$  are the temperature range in which the process operates and  $C_p$  is the specific heat capacity at constant pressure.

$$Q = m \int_{T_1}^{T_2} C_p dT \quad (1)$$

The LHS systems stored/released thermal energy during the phase transition of the storage material from solid to liquid (known as charging), or from liquid to solid (known as discharging). The LHS material is commonly referred to as phase change material (PCM). LHS is preferred over sensible heat storage due to the large quantity of energy available at a fairly constant temperature<sup>[9]</sup>. The storage capacity of a latent heat storage system can be determined using

equation 2 <sup>[8]</sup>, where  $Q$  is the latent heat stored in the system,  $m$  is the mass of storage material,  $T_m$  is the melting temperature of storage material,  $\Delta h$  is the enthalpy or latent heat of storage material,  $T_1$  and  $T_2$  represent the temperature range and  $C_p$  is the specific heat capacity at constant pressure.

$$Q = m \left[ \int_{T_1}^{T_m} C_{p_{solid}} dT + \Delta h + \int_{T_m}^{T_2} C_{p_{liquid}} dT \right] \quad (2)$$

Thermal energy is equally absorbed or released in the form of bond energy of a reversible chemical reaction when the molecular bonds in the material are broken and reformed during an endothermic or exothermic reaction, this type of energy storage is called thermochemical storage <sup>[10]</sup>. Due to the high cost of thermochemical storage systems, their applications are very limited <sup>[6]</sup>. The storage capacity of a thermochemical storage system is given by equation 3 <sup>[11]</sup>, where  $Q$  is the thermo-chemical energy stored,  $m$  is the mass of storage material,  $a_r$  is the extent of conversion and  $\Delta h$  is the endothermic heat of the reaction.

$$Q = m a_r \Delta h \quad (3)$$

TES systems are also classified into high and low-temperature systems depending on the operating temperature range. If the operating temperature is below 250°C, the TES is a low-temperature system, otherwise, it is a high-temperature system <sup>[12]</sup>. Low-temperature TES systems are used in cooling and heating applications of buildings whereas high-temperature TES systems are mostly found in thermal power systems and waste heat recovery. Figure 1 shows the various types of TES <sup>[13]</sup>.

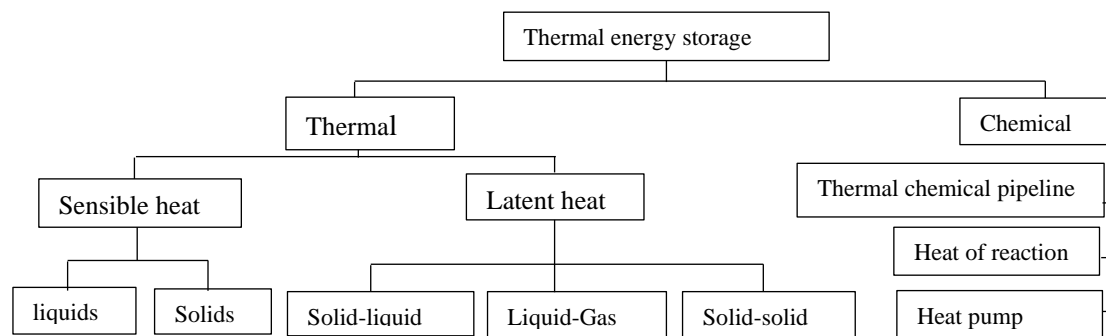


Figure 1: Various types of TES <sup>[13]</sup>

## B. Phase Change Material

A Phase Change Material (PCM) is a substance having a high heat of fusion which, on melting and solidifying at a constant temperature is capable of storing and releasing a large quantity of energy <sup>[14]</sup>. PCMs are, therefore, latent heat energy storage materials that undergo a solid-liquid phase transition at a specific temperature known as the phase transition temperature <sup>[15]</sup>. Thermal energy is absorbed when the PCM material changes from solid to liquid and it is released when the PCM changes from liquid to solid. Solid-liquid PCM are classified into three major groups depending on their composition and the physical transformation for heat-absorbing and desorbing capabilities <sup>[16]</sup>. The classes, as depicted in Figure 2, are organic PCMs, inorganic PCMs and eutectic PCMs.

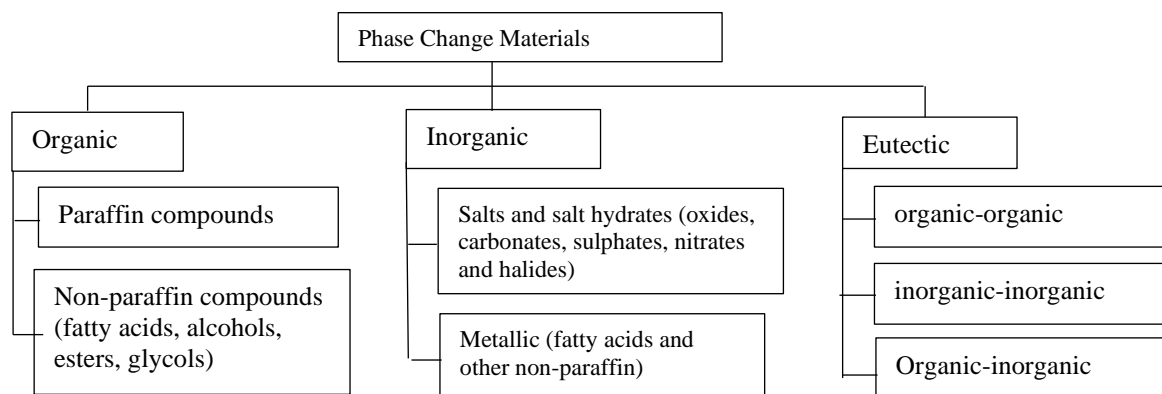


Figure 2: Classification of PCMs <sup>[16]</sup>

Organic PCMs do not exhibit phase segregation during melting and solidifying. They crystallize with little or no super-cooling and are usually non-corrosive. They are mostly inflammable with low thermal conductivity, low flash points and

high heat of fusion. They are unstable at high temperatures. Organic PCMs include paraffin wax and non-paraffin PCMs. The Paraffin waxes consist of a mixture of straight-chain alkenes. The latent heat of fusion increases with chain length. Paraffin is safe, reliable, predictable, less expensive, non-corrosive, and is available in a wide temperature range (5 – 80 °C). On the other hand, non-paraffin organic PCMs include esters, fatty acids, alcohols, and glycols <sup>[13]</sup>.

Inorganic PCMs permit high-density storage because they have high volumetric latent heat storage capacity and their conductivity may be twice as high as that of organic materials. Inorganic PCMs include salts hydrates, salts, metals, and alloys. These PCMs do not supercool appreciably and their heats of fusion do not degrade with cycling <sup>[17]</sup>. A eutectic PCM is a high-breed of two or more components, each of which melts and freezes congruently forming a mixture of the component crystals during solidification. A large number of eutectics of inorganic and organic compounds have been reported <sup>[13]</sup>. Eutectics are generally better than straight inorganic PCMs

## II. MATERIAL SELECTION

### A. Selection of PCM

Two organic PCMs, glycerine and formic acid, were considered for selection for the storage heater. Glycerine is a simple polyol compound. It is a colourless, odourless, viscous liquid that is sweet-tasting and non-toxic. On the other hand, formic acid is the simplest carboxylic acid with the chemical formula CH<sub>2</sub>O<sub>2</sub>. The two PCMs were readily available. The properties of the two PCMs considered for selection are shown in Table I. Glycerine was eventually selected because it is odourless, whereas, formic acid has a pungent smell. An easy way to comply with the conference paper formatting requirements is to use this document as a template and simply type your text into it.

**TABLE I PROPERTIES OF GLYCERINE AND FORMIC ACID**

<b>Property</b>	<b>Glycerine</b>	<b>Formic acid</b>
Chemical formula	C <sub>3</sub> H <sub>8</sub> O <sub>3</sub>	CH <sub>2</sub> O <sub>2</sub>
Molar mass (g/mol)	92.094	46.025
Appearance	Colourless liquid	Colourless liquid
Odour	Odourless	Pungent, penetrating
Density (g/cm <sup>3</sup> )	1.261	1.22
Melting temperature (°C)	17.8	8.4
Boiling temperature (°C)	290	100.8
Latent Heat of fusion (kJ/kg)	198.7	247
Heat Capacity (J/mol. K)	221.9 (at 25 °C), 2.43 kJ/kg.K	101.3 (at 20-100 °C)
Toxicity	Non-toxic	-

### B. Material of Construction

Two materials, Stainless steel and aluminium, were considered for the selection and fabrication of the solar room heater. The properties of the two materials, shown in Table II, are favourable for the solar room heater. However, stainless steel was eventually chosen for easy welding as against aluminium where riveting was the available joining method and is prone to leakages.

**TABLE II PROPERTIES OF MATERIALS CONSIDERED FOR SELECTION**

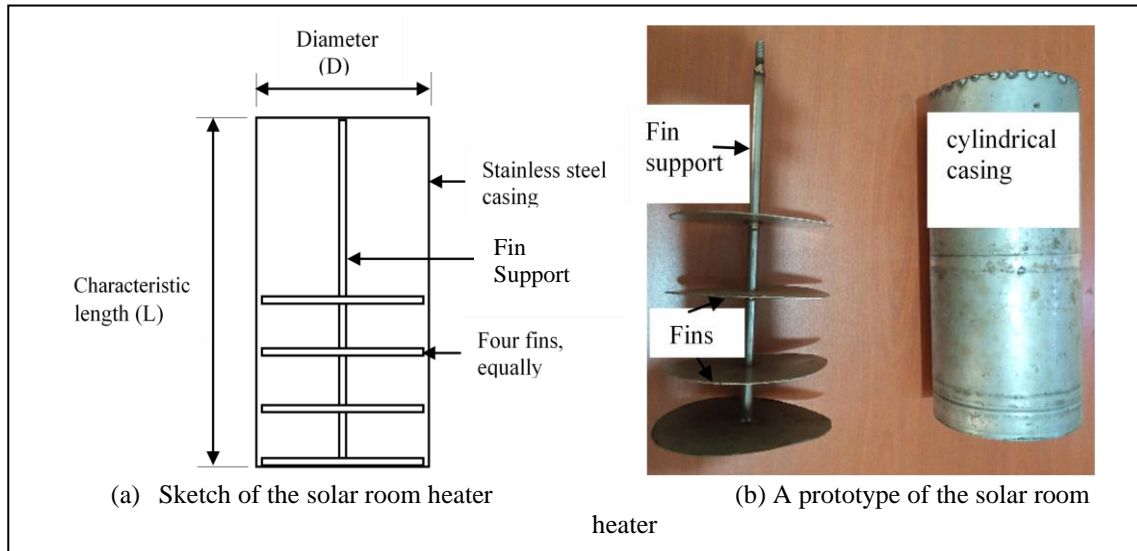
<b>Property</b>	<b>Stainless Steel</b>	<b>Aluminium</b>
Density	8.0 g/cm <sup>3</sup> (8,000 kg/m <sup>3</sup> )	2.7 g/cm <sup>3</sup>
Melting point	1450 °C	660.32 °C
Modulus of Elasticity	193 GPa	76 GPa
Electric Resistivity	0.72 × 10 <sup>-6</sup> Ωm	26.5 × 10 <sup>-9</sup> Ωm
Thermal conductivity	16.2 W/mK	237 W/mK
Thermal Expansion	17.2 × 10 <sup>-6</sup> m/mK	23.1 × 10 <sup>-6</sup> m/mK

### C. Design and Fabrication

Four prototypes of solar room heaters (Type A, Type B, Type C and Type D) were designed and fabricated. To ensure that the solar room heaters are portable, the mass of the PCM material was considered as the basis for the design. 5.5, 4.75, 4.6 and 4.0 kg of the PCM materials were used to determine the dimension of the solar room heater. Stainless steel was selected as the construction material. Even though it is heavier, the former was selected over the latter for easy welding of parts as against riveting. The design specifications of the four solar room heaters are shown in Table III. A sketch, as well as a photograph of the prototype solar room heater, are shown in the Figure 3.

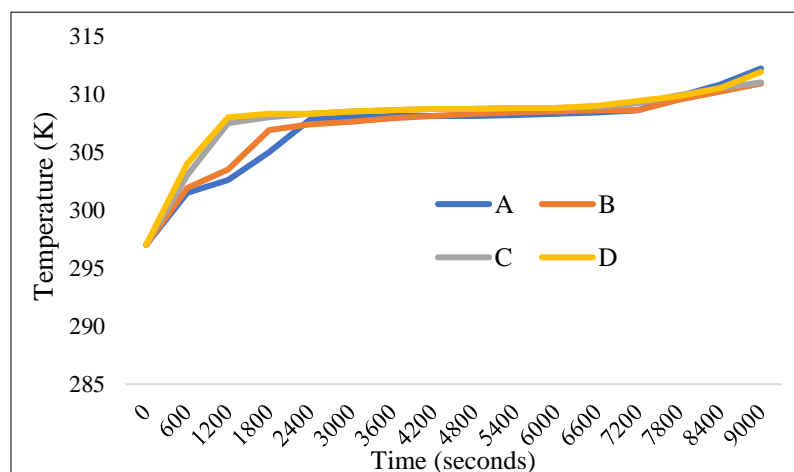
**TABLE III STORAGE HEATER DESIGN SPECIFICATION**

Properties	Type A	Type B	Type C	Type D
Mass of PCM (kg)	5.5	4.75	4.0	4.6
Capacity of storage heater (L)	5.3	4.58	3.86	4.44
Diameter of storage heater (cm)	15.2	15.0	15.0	16
Length of storage heater (cm)	30.4	26	22	22
L/D ratio	9.63	2.85	7.70	2.28
Thickness of material (mm)	1.5	1.5	1.5	1.5


**Figure 3: Prototype solar room heater (a) sketch drawing, (b) photographs**

### III. RESULT AND DISCUSSION

#### A. Charging Period


**Figure 4: Temperature profile during the charging**

The average of the three closest temperature readings obtained during charging of the room heaters was computed and presented as a temperature profile in Figure 4. The total charging period is 7200 seconds (2 hours). The characteristics lengths of the room heaters are 30.4 cm, 26 cm, 22 cm and 22 cm respectively while the capacities of the PCM in the four heaters were 4.5 L, 3.9 L, 3.3 L and 3.8 L respectively. The duration for the PCM in the solar room heater to melt completely (charging period) varied among the four-room heaters. The melting time, extrapolated from Figure 4 and

shown in Figure 5, was 1 hr 40 min, 1 hr 30 min, 1hr 40 min, and 1hr 20 min, for Type A, Type B, Type C and Type D, respectively. Except for the Type B heater, the melting time for the PCMs increases with an increase in the characteristic length of the room heater. However, there is no regular pattern for the effect of PCM capacity on the charging period of the room heater (melting of PCM) as shown in Figure 6.

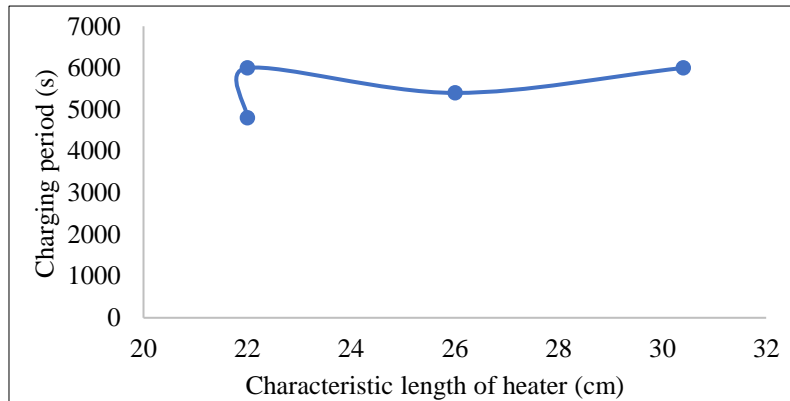


Figure 5: Charging period versus characteristic length of the heater

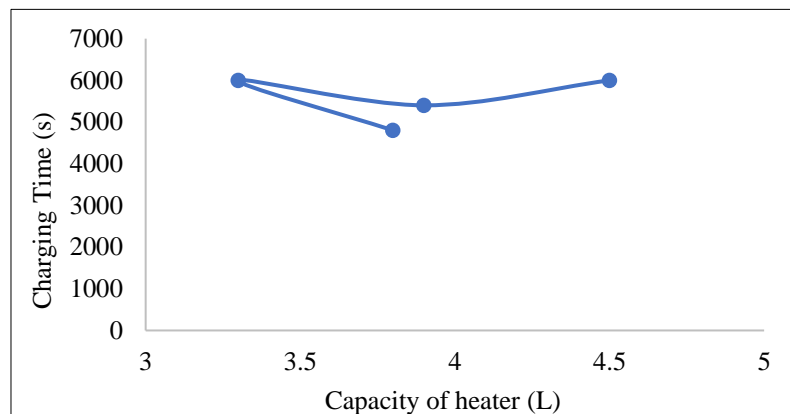


Figure 6: Charging period versus capacity of heater

### B. Discharging Period

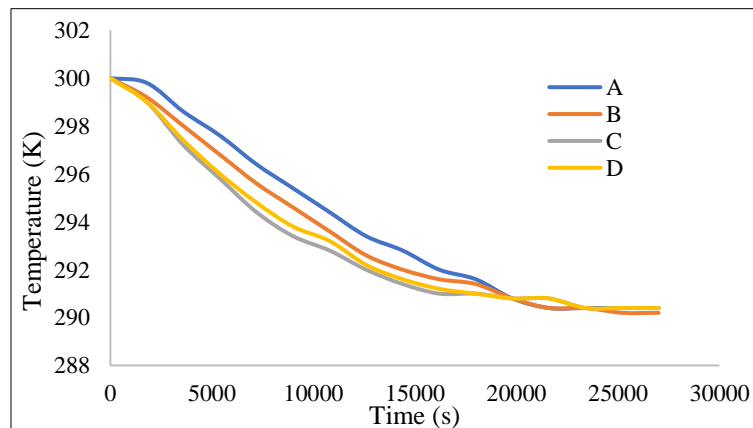


Figure 7: Temperature profile during discharge

The temperature of the solar room heater during discharge was monitored with time. The average of the three closely related readings was computed and presented in Figure 7. The variation of temperature with time revealed that the solar room heater took approximately 25,000 seconds (6 hr 57 min) to completely solidified. The state change was assumed due to the very little drop in temperature in a long duration of time, i.e., 5,000 seconds (or 1 hr 23 sec). The temperature drop with time is lowest in Type A and highest in Type C room heaters.

#### C. Energy Absorption Capacity

The quantity of heat energy absorbed during charging of the solar room heater is categorized into three

1. The quantity of heat absorbed to bring the material to the melting temperature is given by  $Q_1 = mc_p(T_2 - T_1)$
2. The quantity of heat absorbed during the melting of the material is given by  $Q_2 = mL$
3. The quantity of heat absorbed to bring the melted material to the final temperature is given by  $Q_3 = mc_p(T_3 - T_2)$

The total quantity of heat absorbed during charging is thus;  $Q = Q_1 + Q_2 + Q_3$

The energy absorption capacity of the solar room heater is given as;

$$\frac{Q}{t_T} = \frac{Q_1}{t_1} + \frac{Q_2}{t_2} + \frac{Q_3}{t_3}$$

where  $m$  is the mass of the PCM,  $c_p$  is the specific heat of the PCM,  $T_1$  is the initial temperature of the room heater,  $T_2$  is the melting temperature of the PCM,  $T_3$  is the final temperature of the room heater,  $L$  is the latent heat of fusion of the PCM,  $t_1$  is the time taken for the temperature of the room heater to rise from  $T_1$  to  $T_2$ ,  $t_2$  is the time taken when the temperature of the room heater maintain at  $T_2$ , and  $t_3$  is the time taken for the temperature of the room heater to rise from  $T_2$  to  $T_3$ .

The energy absorption capacities of the four prototype solar room heaters, as well as their heat transfer areas, are shown in Table IV. Type A room heater, having the highest heat transfer area, has the highest energy absorption capacity while Type C room heater, having the lowest heat transfer area, has the lowest energy absorption capacity. Even though Type D has a higher diameter than Type B, the energy absorption capacity of Type B is higher due to a higher heat transfer area and higher length.

**TABLE IV ENERGY ABSORPTION CAPACITY OF SOLAR ROOM HEATER**

	Type A	Type B	Type C	Type D
Sensible heat 1 ( $Q_1$ ) (J/s)	61.26	64.13	89.1	102.5
Latent heat ( $Q_2$ ) (J/s)	227.68	174.78	132.47	169.26
Sensible heat 2 ( $Q_3$ ) (J/s)	29.7	25.65	16.2	18.63
Total heat (J/s)	318.64	264.56	237.77	290.39
Heat transfer area ( $m^2$ )	0.1633	0.1402	0.1213	0.1307

#### IV. CONCLUSION

Four prototypes of solar room heaters were developed using glycerin as the PCM material and stainless steel as heat transfer material. The dimensions of the prototypes solar room heaters were Type A (diameter = 15.2 cm, length = 30.4 cm), Type B (diameter = 15.0 cm, length = 26.0 cm), Type C (diameter = 15.0 cm, length = 22.0 cm) and Type D (diameter = 16.0 cm, length = 22.0 cm). The average charging period for the solar room heaters was Type A (1 hour 40 minutes), Type B (1 hour 30 minutes), Type C (1 hour 40 minutes) and Type D (1 hour 20 minutes). The average discharging period for the solar room heater was approximately 25,000 seconds (6 hour 57 min). The duration for the charging and the discharging of the room heater has a positive linear relationship with the volume of the phase change material.

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