VFAST Transactions on Mathematics
http://vfast.org/journals/index.php/VTM@ 2021, ISSN(e): 2309-0022, ISSN(p): 2411-6343
Volume 10, Number 2, July-December, 2022 *pp: 186-199*

The melting behavior of Paraffin RT-50 in a finned cylindrical surface

Waris Ali^{1,2}**, Asif Ali Shaikh**^{1}**, Feroz Shah**^{1}**, Sajjad Hussain**^{3,4,*}

^{1}Deptt of BSRS, Mehran Uni of Engg and Tech, Jamshoro, Pakistan; ^{2}Presently: Department of Mathematics, University of Education Lahore, Multan Campus, Punjab, Pakistan.; ^{3,*}School of Mechanical and Aerospace Engineering, Nanyang Technological University, Singapore. ; ^{4} Department of Mathematics, Govt Postgraduate College Layyah, Punjab, Pakistan.

Keywords: *Cylindrical surface, Rubitherm-50, thermocouples, PCM, latent heat transmission, melting phenomenon, metallic fins.* ***Subject Classification***: *Fluid dynamics*

Journal Info:
Submitted:
November 21, 2022
Accepted:
December 23, 2022
Published:
December 31, 2022

Abstract The energy provision is one of the main concerns of modern technological processes and thermal management systems. Through latent heat energy, the storage of thermal energy using phase-change materials is examined in this paper. Paraffin Rubitherm 50 is filled in the cylinder. The base of the cylinder is heated and the vertical surface is made adiabatic. The melting procedure for two cases namely the plane surface and finned surface of the cylinder are considered. The melt fractions are observed and photographed for fixed intervals of time from solid state to total melt state. Initially, the melting of specified PCM was slow and then it became faster when convection heat transfer is accompanied with the conduction. The melting of PCM is geared with fin presence.

***Correspondence Author Email Address:**
email1@example.com (sajjadgut@gmail.com)

1 Introduction

Phase change materials (PCM) employ a latent heat storage system that offers the advantages of high storage density and isothermal storage. It has been established that choosing the right PCM is just as important to the success of a latent heat-storage mechanism as selecting the appropriate heat transmission system.

The importance of thermal storage systems developed for HVAC (heating, ventilation, and air conditioning) applications and hot water preparation is growing as a result of the depletion of fossil fuels and the need to protect the environment.

Thermal storage may be used in HVAC applications to accommodate storage at several temperatures linked to cooling and heating activities. High temperature storage is frequently related to solar energy, the use of waste heat, or applications involving heat pumps, whereas cool storage is usually related to operations involving air conditioning or cryogenic temperatures. For a very long time, scientists have been working on a technique that can be utilized to supply heat or cold in a specific volume. British trains were the first to adopt phase-change materials to keep them from getting too chilly. Applications by Telkes in 1975 and Lane in 1986 for heating and cooling in buildings were the first reports of a PCM that were written about in the literature. Although Telkes first proposed the idea, PCM walls are more commonly referred to as Trombe walls. Additionally, PCMs have been created to store "coolness" for air conditioning applications. The "cold" is gathered in the PCM over the course of the night before being used to cool a building's interior during the hottest times of the day. There are distinct ways to advance the flow of heat because PCMs have poor thermal conduction.

Latent heat storage materials and systems are widely studied and are a vast quantity of information available about them. Sharma et al. [1] compiled data from prior studies on PCMs and latent heat storage systems. The numerous heat transfer improvement approaches for latent thermal energy storage systems (LHTS) systems are reviewed by Velraj et al. [2]. Jegadheeswaran and Pohekar [3] examined the application of diverse strategies in various LHTS system configurations. Using phase-change materials, Nomura et al. [4] outlined the research trends in latent heat storage methods (PCMs). Thermal Analysis and Differential Scanning Calorimetry are used by Abhat [5] to analyze the melting behavior of diverse substances. Hawes et al. [6] look at how well gypsum wallboard and concrete blocks impregnated with PCMs perform. Mettawee et al [7] research investigated if adding aluminum powder would improve the heat conductivity of paraffin wax. The geometry and designs of PCM containers were examined by Agyenim et al. [8], along with several computational and experimental investigations to scrutinize the possessions of variables like intake temperature and heat transfer fluid mass flow rate (HTF). It has been proven that while designing a latent heat storage system, the PCM selection is equally crucial to the system's success as the heat transmission mechanism. The importance of thermal systems developed for HVAC applications and hot water preparation is growing as a upshot of the depletion of fossil fuels and the need to protect the environment.

Thermal storage may be used in HVAC applications to accommodate storage at innumerable temperatures linked to cooling activities. Typically, the heat transfer fluid serves as a material for heat exchange between a heat source and a PCM, is used to store thermal energy. Most frequently, heat transfer fluids use a heat exchanger to transfer heat to PCM. However, the majority of PCMs have poor thermal conductivity, which makes moving heat inside the PCM difficult. In order to effectively store and extract thermal energy in these systems, heat transfer improvement becomes crucial. The PCMs are divided into four subgroups: fatty acids, commercial PCMs, organic PCMs, and inorganic PCMs. Recently, the need for more energy-efficient systems has spurred interest in the storage of latent energy in phase transition materials. During times of high load, free cooling and heat can be saved and used later. The supply-load gap can be filled as a result. Since phase change materials (PCM) require a lot less room to store the same amount of energy as an equal water cistern, they are an efficient method for providing heating and cooling to buildings. Advanced heat transfer design can compensate for the low thermal conductivity of the majority of PCMs; however, the effects of the various heat transfer mechanisms are not specifically examined. In addition to pure compounds, distinct phase transition temperatures may also be produced by eutectic combinations of compounds. The literature is replete with details on PCMs. The chemical assets of the PCM utilized to affect the design and functioning of latent heat thermal storage. For each suggested application, a lower storage capacity is needed, the greater the PCM's energy density. Heat transfer is a type of thermal energy that happens when there is a temperature differential during transit. Among all of the systems in an automobile, the cooling system is one of the most crucial. Fins are in charge of transferring the heat generated inside the cylinder through a variety of processes, including conduction, convection, and radiation. Engine cooling fins conduct conduction from these modes. Maji and Cubey et al. [11] looked at the expanded surfaces or fins to enhance heat transmission. The findings of a computer analysis of airflow and heat transfer in a lightweight vehicle engine using three various pin fin morphologies were presented by Sanjay and Vikas et al. [12]. D. Talor and J. Talor [13] examined the transient analysis of fins with complex shapes. Keyes [14] talked about a unique arrangement for cooling silicon devices that allows water to flow through etched fins. Sathishkumar et al. [15] used computer tools to investigate heat transmission through fins. Natural convection heat transfer from vertical rectangular fin arrays was investigated by Barhatte et al. [16]. Verma and Gautam [17] conducted the review analysis employing fins in a variety of applications to achieve the highest heat transfer rate. Thermal analysis of the mechanics of heat transfer through porous fin was examined by Deshamukhya et al.[18]. Wood et al. [19] give a comparison of various models made up of a connected extended surface and the main surface (wall). Kiwan et al. [20] introduced by the ground-breaking method that uses porous fins to increase heat transmission.

A glance at the relevant existing studies as revised above that thermal energy storage (TES) consisting of cylindrical container is rarely considered till the recent past. The cylindrical TES is simple configuration, it can easily be handled and modified according to required mode of application. The axial symmetry makes it preferable in three-dimensional operating scenarios. Here, the natural convection is accelerated in the upper sections and the heat transfer is weakened in the bottom when charging takes place. The objective of thermal energy storage is attained which is radially available for later use. The melt fractions are captured at regular intervals for plan inner surface and finned surface. The temperature variation is measured at three places. A pure PCM is RT. Here, a heat storage material makes use of the melting and congealing processes of solid-liquid phase transition to store huge amounts of thermal energy at a practically fixed temperature.

2 Physical description of problem

Consider the PCM (RT-50) melting in a cylindrical container with height $73mm$ and diameter $49mm$. The cylindrical surface is made from stainless steel sheet of width and the base of the cylinder is made of copper sheet of thickness $0.6mm$. Rectangular coordinate system is chosen the origin is fixed at the center of the base. A heater of AC voltage $12V$ with dry heating temperature level of $90^0C(\pm)10^0C$ is fixed at the bottom of the cylinder. The thermophysical properties of PCM are enlisted in Table. 1. In order to note the variation of melt fraction, three thermocouples C_1, C_2 and C_3 are respectively fixed in the interior of cylindrical container at $(16mm, 0, 50mm)$, $(-16mm, 0, 47mm)$ and $(0, 15mm, 50mm)$. The melting of the PCM is studied into two configurations; case 1: without fin case, case 2: with fin, as shown in figures 1(a) and 1(b) respectively. Two fins $(60 \times 1mm^2)$ are adjusted at the positions $(0, 0, 60mm)$ and $(0, -12mm, 60mm)$ geared with fin operation. The two designs of the physical configuration are captured in Fig. 1(a) and Fig. 1(b) without fins and with fins respectively. Equation for mass, momentum, and energy may be written

(a) Geometry of problem without fin

(b) Geometry of problem with fin

as [21, 22]:

$$\nabla.u = 0, \tag{1}$$

$$\frac{\rho}{\epsilon_p}\frac{\partial u}{\partial t} + \frac{\rho}{\epsilon_p^2}(u.\nabla)u = \nabla.[-pI + K'] - \frac{\mu}{k}u, \tag{2}$$

$$\rho C_p\frac{\partial T}{\partial t} + \rho C_p u.\nabla T = \nabla.(k\nabla T), \tag{3}$$

$$K' = \frac{\mu}{\epsilon_p}[\nabla u + (\nabla u)^T], \tag{4}$$

Kozeny-Carman's permeability model is as followed:

$$k = \frac{d_p^2\epsilon_p^2}{180(1-\epsilon_p)^2}, \tag{5}$$

When small volumes and small temperature changes are present, phase change materials (PCMs) offer a very efficient way to store heat and cold.

Modes for storing energy Energy can be stored in a variety of methods, including:

- Mechanical energyl storage
- Battery storage
- Thermal energy storage (TES)

Each of these technologies has advantages and disadvantages. The fact that TES is a relatively simple and secure method of energy storage is one of its benefits. While LHTES stores energy through the phase change of a substance, SHTES does so by altering the temperature of a solid or liquid. Phase shifts can occur from solid to liquid, solid to solid, solid to gas, or solid to gas, liquid to gas, and vice versa. **Classifications and features of PCM** The PCMs can be categorized into three sections:

1. eutectic,
2. inorganic, and
3. organic.

Two or more organic and/or inorganic PCM components make up eutectic PCMs, the first class of PCMs. Inorganic PCM is further classified into metallics and salt hydrates, while organic PCM is further classified into paraffin and non-paraffins. The benefits of paraffin wax include reliability, safety, and a lack of corrosivity. These restrictions are brought on by paraffin's poor compatibility with plastic containers and limited heat conductivity. For accurate heat transfer predictions, convection may need to be taken into account depending on the kind and form of the heat exchanger as well as the properties of the PCM, such as whether it is crystalline, gelled, or not.

Prospective PCM implementation areas There are numerous instances where a system's efficiency could be further improved by employing PCM. Examples of applications for PCMs include

- Thermal energy storage in heat exchangers.
- Incorporated directly into a building's walls, roof, or floors.
- Electricity storage for off-peak times; solar water and air heating systems.

It has been looked at from a variety of perspectives whether PCM may be built directly into the structural framework of buildings, acting as a temperature regulator. Buildings with thinner walls or floors can be advantageous because they weigh less overall. After all, PCMs have a high heat storage density.
Properties for RT-50 [23]:

- Long-lasting product with consistent performance across phase change cycles.
- large capacity for thermal energy storage.
- heat is stored and released at comparatively constant temperatures.
- chemically inert.
- melting temperature range between -9 $^\circ[C]$- 100 $^\circ[C]$ available.

Table 2: Thermophysical properties of PCM are given below:

Thermophysical properties	Typical values	Measurable Units
Melting area	45 – 51mean peak:49	$[{}^\circ C]$
Congealing area	51 – 46mean peak:50	$[{}^\circ C]$
Heat storage capacity $\mp$ 7, 5percent	160	$\left[\frac{kJ}{kg}\right]$
Combination of latent and sensible heat		
in a temperature43^0C – 58^0C	46	$\left[\frac{Wh}{kg}\right]$
Specific heat capacity	2	$\left[\frac{kJ}{kgK}\right]$
Density solid	0, 88	$\left[\frac{kg}{l}\right]$
Density liquid	0, 76	$\left[\frac{kg}{l}\right]$
Heat conductivity (both phases)	0, 2	$\left[\frac{W}{m.k}\right]$
Volume expansion	12, 5	$\left[\circ / \circ\right]$
Flash point	Greater than 200	$\left[{}^0C\right]$
Max. operation temperature	70	$\left[{}^0C\right]$

In the PCM, a phase change function α is specified, phase change heat transfer takes place. The values of phase change function α gives value zero for temperatures below $\left(T_m - \frac{\Delta T_m}{2}\right)$ to 1 for temperatures above $\left(T_m - \frac{\Delta T_m}{2}\right)$ .i.e., phase change arises for the range between $\left(T_m - \frac{\Delta T_m}{2}\right)$ and $\left(T_m + \frac{\Delta T_m}{2}\right)$. The energy equations during phase change are indicated in Eq. (3), whereas thermo-physical properties change according to [22]:

$$\theta = 1 - \alpha, \tag{6}$$

$$\rho = \theta\rho_{f_2} + (1 - \theta)\rho_{f_2}, \tag{7}$$

$$C_p = \frac{1}{\rho}\left[\theta\rho_{f_1}C_{p,f_1} + (1 - \theta)\rho_{f_2}C_{p,f_1}\right] + L\frac{\partial\alpha_m}{\partial T}, \tag{8}$$

$$k = \theta k_{f_1} + (1 - \theta)k_{f_2}, \tag{9}$$

$$\alpha_m = \frac{\theta\rho_{f_1} + (1 - \theta)\rho_{f_2}}{2(\theta\rho_{f_1} + (1 - \theta)\rho_{f_2})}. \tag{10}$$

where L stands for the the latent heat of fusion and sub-indices f_1 and f_2 represent the first and second phases, respectively.

Table 2: The camera specifications are listed below:

Camera Lenz features	Measurements
Telephoto	aperture f/2.8
Wide	aperture f/1.5
Ultra-wide	aperture f/1.8
field of view	120^0
optical zoom in	$3x$
optical zoom out	$2x$
optical zoom range	$6x$
Digital zoom	up to$15x$

3 Discussion

The purpose of this study is to investigate the heat transfer processes in a finned cylindrical PCM heat exchanger to carry out an advanced heat transfer analysis for a phase change thermal energy storage system. Assessing the impact of convection-induced heat transport in a PCM that isn't gelled will be the main focus. A numerical model that matches the model used in the actual tests must be created. To ensure the accuracy of the numerical model and to adapt the numerical models to the experimental data, parametric research is required. To provide the necessary theory for the numerical models and to provide this study with an overview of PCMs as a heat storage technology, a literature review is also included in the work. The observations of the melting are captured in pictorial form by using camera of iPhone 13Pro Max. Its features are presented in Table 2. All the pics are taken at the distance 195mm from the base of the cylinder. The records of the findings are maintained with the snapshoots of 5min(300min). In this study, experimental design is used to analyze the temperature distribution and thermal performance of a three-dimensional vertical cylinder filled with PCM. Convection and conduction effects are present. In Figs. (2a-4d), the heat transfer and melting of PCM is checked without fins and later in Figs. (5a-7b) melting phenomena is analyzed with fins. Fig. (2a-4d) display the phase fluctuation for time variation $t = 0$ to $t = 3300sec$. For this arrangement, phase transition takes place over time inside the container. Initially, the melting begins at the bottom due to conduction and then it spreads along the sides of surface. From Fig. (2c) when $t = 600sec$ the liquid fraction becomes sizeable. With the passage of time, melting speeds up and the liquid fractions seems to increase (see Figs. (2d-3c)). In the meanwhile, convection processes are started and the heat transfer become faster and the heat is transferred inside the PCM. It is seen that oval circulations arises in the liquid portion. Fig. (3d) and Fig. (4a) exhibit the fast-reducing patterns of solid fraction respectively for time $t = 2100sec$ and $t = 2400sec$. When time approaches $t > 2400sec$, a full phase transition takes place. However, there are certain spots of messy zones as depicted in Fig. (4b) and Fig. (4c). Total melt of PCM for the simple cylinder without fins is attained at $t = 3300sec$ as captured in Fig. (4d).

The melting of PCM has been observed for the finned cylindrical surface. Fig. (5a) depicts the PCM filled cylinder at $t = 0$. The liquid fractions can be noticed along the curved surface after $t = 300sec$ (as shown in Fig. (5b)). Moreover, as fin at position $(0, -12mm, 60mm)$ near the bottom seems hotter than the fin at position $(0, 0, 60mm)$. The conduction of heat due to surfaces and fins plays its role to transmit the thermal distribution. The melt fraction increases due to convection for increasing liquid phase as observed in Figs. (5c-6b) when time extend from $600sec$ to $1500sec$. In these figs, the heat transfer due to the first fin at $(0, -12mm, 60mm)$ play a prominent role to enhance the melting of PCM. In Fig. (6c), the second fin at $(0, 0, 60mm)$ also transmits heat and solid fraction remains near the fins. It is seen that fast melting of PCM takes place (see Figs. (6d) and (7a)) for $2100sec$ to $2400sec$. Finally, Fig. (7b) captures at whole of the PCM has melted at $2700sec$. Thus, the total melt of PCM for finned surface takes place $600sec$ before that of the case without fins. The extended structure plays advantageous role for the melting of PCM to transfer heat vastly the container. Fig. (8a) and Fig. (9a) presents graphical situation of temperature distribution for plane cylinder and the finned cylinder as indicated by three sensors. It is noticed from both of plots that heat energy is stored by PCM for nearly 1980sec ($33minutes$). Then, the temperature starts rising. The substantial storage of energy is computed from the relation as below:

$$E_Q = \frac{Q}{t}, \tag{11}$$

where E_Q is ratio of total energy storage $\left(\frac{J}{S}\right)$, Q is the energy storage capacity (J) of PCM and t is the charging time.

(a) Without fin with $t = 0$ min(0 sec)

(b) Without fin with $t = 5$ min(300 sec)

(c) Without fin with $t = 10$ min(600 sec)

(d) Without fin with $t = 15$ min(900 sec)

(a) Without fin with $t = 20$ min(1200 sec)

(b) Without fin with $t = 25$ min(1500 sec)

(c) Without fin with $t = 30$ min(1800 sec)

(d) Without fin with $t = 35$ min(2100 sec)

(a) Without fin with $t = 40$ min(2400 sec)

(b) Without fin with $t = 45$ min(2700 sec)

(c) Without fin with $t = 50$ min(3000 sec)

(d) Without fin with $t = 55$ min(3300 sec)

(a) With fin with $t = 0$ min(0 sec)

(b) With fin with $t = 5$ min(300 sec)

(c) With fin with $t = 10$ min(600 sec)

(d) With fin with $t = 15$ min(900 sec)

(a) With fin with $t = 20$ min(1200 sec)

(b) With fin with $t = 25$ min(1500 sec)

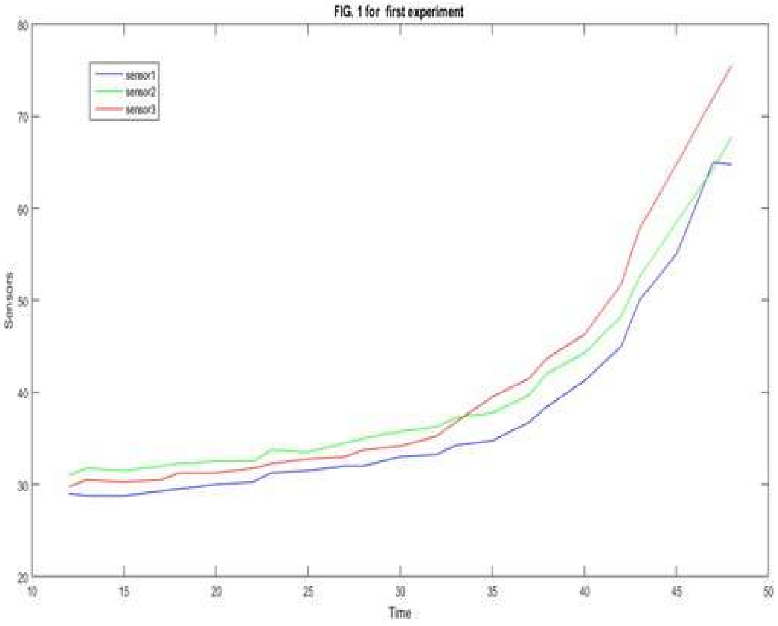
(c) With fin with $t = 30$ min(1800 sec)

(d) With fin with $t = 35$ min(2100 sec)

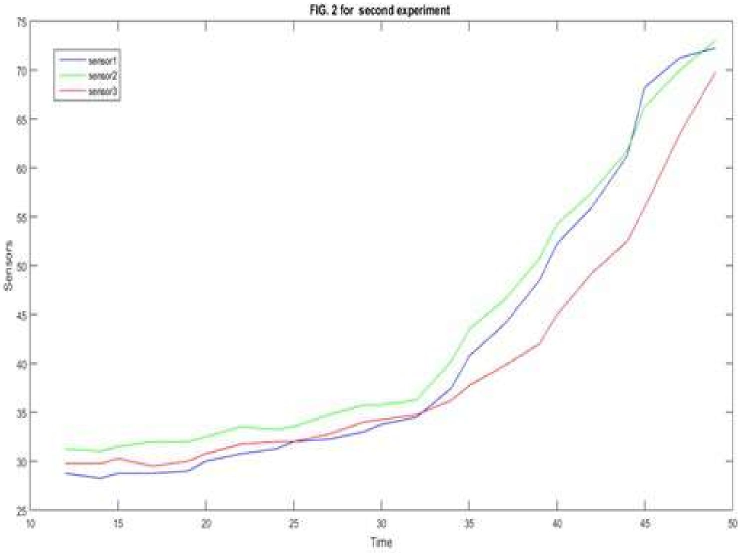
(a) With fin with t = 40 min(2400 sec)

(b) With fin with t = 45 min(2700 sec)

Temperature variation of PCM with time at heat input are presented below:



(a) Results of sensors over time without fins



(a) Results of sensors over time with fins

4 Conclusion

The PCM's properties, such as the required temperature range, the compatibility of the container with the PCM, and the best heat exchanger for providing adequate efficient heat transfer. This is required because the heat transfer processes of the PCM must be properly understood to identify the appropriate heat exchanger design. In this framework, heat energy storage of phase change material (PCM) RT-50 confined in cylindrical surfaces are considered. Two parts of the study for the simple cylinder and for finned surface are undertaken. A heat source is supplied at the bottom of cylinder. The charging time for finned surface is 2700*sec* and there for phase surface is 3300*sec*. Also, the heat distribution is different in the cases.

Author Contributions

Feroz Shah: Conceptualization, Methodology, Software **Feroz Shan**: Data curation, Writing- Original draft preparation. **Asif Ali Shaikh**:Supervision. **Sajjad Hussain**: Writing- Reviewing and Editing.

Compliance with Ethical Standards

All writers have stated that they have no conflicts of interest. Additionally, it is stated that none of the writers of this article conducted any experiments on human subjects or animals for this article. Furthermore, each participant who took part in the study gave their free, informed permission.

Funding Information

FMS acknowledges the support of NSF grant CHE-1111111.

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