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**Numerical investigation of phase
change material melting in horizontal
annular system: Effect of eccentricity**

Presented by:
BOUZNAD Abdelkhalek Amar

Supported on:

Before the jury composed of:

I. TABET	MCA	University of Skikda	President
N. BOULAKTOUT	MCB	University of Skikda	Protractor
	MRA	University of Skikda	Co-Rapporteur
K. DHIF	MAA	University of Skikda	Examiner

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Dedication

*This work is dedicated to my entire family,
especially to my father, my mother, my sister, my brothers, and my
grandparents.*

*I also extend this dedication to my friends and to all those who are
close to me.*

Acknowledgments

First of all, the completion of this thesis was made possible thanks to God, who gave me the strength to overcome all the challenges throughout my years of study.

I would like to express my sincere gratitude to my supervisor, Dr. Nesrine Boulaktout, for her guidance and continuous support throughout the duration of this work.

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Finally, I extend my heartfelt thanks to all those who contributed, directly or indirectly, to the realization of this thesis.

Abstract

The aim of this study is to investigate the thermal enhancement performance of stearic acid melting in an annular heat tube exchanger system. The study emphasizes the effect of eccentricity on melting dynamics and heat transfer characteristics. A two-dimensional geometry of three configurations was simulated using ANSYS Fluent and the enthalpy-porosity method: a concentric setup and two eccentric configurations with varying offsets. The results reveal that increased eccentricity significantly enhances natural convection, accelerates the melting process, and improves overall heat transfer efficiency, with an optimal geometric configuration enhancing the melting rate by up to 40.5%. These findings demonstrate the importance of geometric optimization in the design of latent heat thermal energy storage systems in horizontal annular systems.

Keywords: Melting, phase change material, horizontal annular system, concentric, eccentric.

Résumé

L'objectif de cette étude est d'analyser la performance d'amélioration thermique de la fusion de l'acide stéarique dans un système d'échangeur de chaleur annulaire. L'étude met l'accent sur l'effet de l'excentricité sur la dynamique de fusion et les caractéristiques de transfert de chaleur. Une géométrie bidimensionnelle de trois configurations a été simulée à l'aide d'ANSYS Fluent et de la méthode enthalpie-porosité: une configuration concentrique et deux configurations excentriques avec des décalages variés. Les résultats révèlent qu'une augmentation de l'excentricité améliore considérablement la convection naturelle, accélère le processus de fusion et accroît l'efficacité globale du transfert thermique, avec une configuration géométrique optimale permettant une augmentation du taux de fusion allant jusqu'à 40,5 %. Ces résultats démontrent l'importance de l'optimisation géométrique dans la conception des systèmes de stockage d'énergie thermique à chaleur latente dans les configurations annulaires horizontales.

Mots clés : Matériau à changement de phase, fusion, système annulaire horizontal, concentrique, excentrique.

الملخص

تهدف هذه الدراسة إلى تحليل أداء التحسين الحراري لعملية انصهار حمض الستياريك داخل نظام مبادل حراري حلقي. وتُرَكِّز الدراسة على تأثير اللامركزية على ديناميكيات الانصهار وخصائص انتقال الحرارة. تم استخدام برنامج ANSYS Fluent وطريقة الإنثالبي-المسامية لمحاكاة هندسة ثنائية الأبعاد بثلاث تكوينات: تكوين مركزي وتكوينان غير مركزيين بانزياحات مختلفة. تكشف النتائج أن زيادة اللامركزية تعزز بشكل كبير الحمل الحراري الطبيعي، وتُسْرِع عملية الانصهار، وتحسّن كفاءة انتقال الحرارة بشكل عام، حيث تساهم التهيئة الهندسية المثلى في زيادة معدل الانصهار بنسبة تصل إلى 40.5%. وتُبرز هذه النتائج أهمية تحسين التصميم الهندسي في أنظمة تخزين الطاقة الحرارية الكامنة في الأنظمة الحلقية الأفقية.

الكلمات المفتاحية: المادة متغيرة الطور، عملية الانصهار، النظام الحلقي الأفقي، التكوين المركزي، التكوين اللامركزي.

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Nomenclature:

Latin letters:

Symboles	Unit	Signification
q''	W/m ²	Heat flux
ΔQ	J	Amount of heat transferred
A	m ²	Surface area through which heat is transferred
Δt	S	Time duration during which heat transfer occurs
q_x	W	Heat transfer rate
$\frac{dT}{dx}$	K/m	Temperature gradient in x-direction
k	W/m·K	Thermal conductivity
A	m ²	Cross-sectional area perpendicular to heat flow
q	W	Heat-transfer rate
A	m ²	Surface area
H	W/m ² ·K	Convection heat transfer coefficient
T_s	K	Surface temperature
T_∞	K	Temperature of the fluid far from the surface
q_r	W	thermal radiation heat transfer rate
A	m ²	Surface area of the radiating body
T	K	Absolute temperature of the surface
$Q_{sensible}$	J	Storage capacity
T_f	K	Final temperature
T_i	K	Initial temperature
M	Kg	The mass of storage material
c_p	J/kg, K	The specific heat capacity
u	m/s	Velocity vector
p	Pa = N/m ² = kg/(m·s ²)	Pressure
g	m/s ²	Gravitational acceleration
S	W/m ³ = J/(s·m ³)	Source term representing phase change effects
H	J/kg	Total enthalpy
K	W/m·K	Thermal conductivity
T	K	Temperature
cp	J/kg·K	Specific heat at constant pressure
L	J/kg	Latent heat of fusion

C Empirical constant

Greek letters:

Σ	$W/m^2 \cdot K^4$	Stefan–Boltzmann constant with a value of $5.67 \cdot 10^{-8}$
ρ	kg/m^3	Density
μ	$kg/m \cdot s$	Dynamic viscosity
Φ		Liquid fraction
ϵ		Small numerical constant to avoid division by zero

Acronyms:

IEA	International Energy Agency
PCM	Phase change materials
TES	Thermal Energy Storage
TESS	Thermal Energy Storage system
LHSS	Latent heat storage systems
K	Kelvin
<i>SI</i>	International System of units
J	Joule
Btu	British thermal unit
Cal	Calorie
MES	Mechanical energy storage
ECES	Electrochemical energy storage
CES	Chemical energy storage
TCS	Thermo chemical storage
SHS	Sensible heat storage
LSH	Latent heat storage
HVAC	Heating, ventilation, and air conditioning
PV	Photovoltaic panels
LHTES	Latent heat thermal energy storage

*General
Introduction*

General Introduction

Every action and transformation in the universe derive from energy, which is a fundamental concept in physics and essential in all aspects of life. From powering cities to enabling biological processes, energy is vital for the research advancement and the prosperity of human-kind. It is defined as the capacity to do work, where “work” refers to applying a force to move an object. Energy may exist in various forms including potential, kinetic, thermal, electrical, chemical and nuclear. And it can be categorized as fossil energy such as coal, oil and natural gas, and renewable energy such as solar, wind, hydroelectric, and geothermal. Whether this energy can meet global energy demand is majorly debated among the researchers. [1].

Energy is a key factor for contributing to the involvement of the humankind in various aspects of life. The increase of energy demand caused by the raising of the living standards and technological advancement, and the world strategy to reduce fossil energy consumption has led researchers and industrialists to seek for an alternative energy source “renewable”. Quoting the International Energy Agency (IEA) report, “Global energy demand grew by 2.2% in 2024 – faster than the average rate over the past decade. Demand for all fuels and technologies expanded in 2024” [2]. One of the major problems that renewable energy sources such as wind or solar is facing, and it is holding it back from competing against fossil energy is efficient storage [3]. Energy storage systems are very important for using energy in a cleaner and smarter way. These systems are transforming the energy sector by tackling key challenges in power generation and distribution [4].

Phase change materials (PCMs) are a class of materials that store latent heat during the melting process and release it during solidification, while maintaining a near constant temperature [14]. This material revolutionizes the thermal energy storage (TES) and latent heat storage systems (LHSS). Today several materials can be classified as a PCM ranging from organic, inorganic and eutectic PCMs, each and every one of these materials have some advantages and challenges such as super-cooling, phase segregation, thermal stratification.

This work focuses on the study of eccentricity effect on the thermal performance of an organic PCM in an annular system.

The context and results of this study are presented here in detail:

Chapter I covers the basic thermal concepts, such as temperature, heat, heat flux, and the different heat transfer mechanisms (conduction, convection and radiation). It also covers some types of energy storage specifically the thermal energy storage modes.

Chapter II focuses on the fundamentals and basic science behind phase change materials starting by a brief history on PCMS, types, properties and applications. It also discusses the latest research trends, as well as bibliographic research.

Chapter III we will dive into the mathematical formulation and numerical modelling of our work where we simulate three different configurations. Also presenting the working assumptions and boundary conditions.

The fourth chapter is dedicated to the presentation, interpretation, and discussion of the results.

Finally, a general conclusion is provided at the end of this document.

Chapter I:

Thermal energy storage

I.1 Introduction

The growing demand for sustainable energy solutions has intensified global interest in thermal energy storage (TES) technologies. Understanding TES begins with a solid foundation in thermal concepts and the fundamental mechanisms of heat transfer conduction, convection, and radiation. This chapter explores these concepts to establish the thermophysical basis for TES systems. It then examines the various methods used to store energy, such as mechanical, electrochemical, chemical, and thermal systems, with a particular emphasis on the mechanisms and benefits of TES, including sensible, latent, and thermochemical storage techniques.

I.2 Thermal concepts and heat transfer

In order to understand the mechanisms of heat transfer, it is essential to define and distinguish between the basic thermal concepts: temperature, heat, and heat flux. That difference lies in their definitions, properties, and role in thermodynamics.

a. Temperature: is a quantitative measure of the degree of hotness or coldness of a substance. It indicates the direction in which thermal energy naturally transfers; that is from a body at a higher temperature to one at a lower temperature. The common scales for measuring temperature are Kelvin (K), in SI (international system of units), Fahrenheit, Rankine, and Celsius [5].

In other words, temperature is a thermodynamic property of a substance that reflects the microscopic motion of its constituent particles. According to kinetic theory, the temperature of a body is directly related to the average translational kinetic energy of its molecules. The kinetic energy of a substance becomes zero at a temperature known as absolute zero [6].

b. Heat: is defined as energy in transit. The transfer of energy in the form of heat occurs at the molecular level due to temperature gradient. Heat can be transmitted through various media: via conduction in solids, through convection in fluids, and through radiation across empty space “void”. Figure I. 1 illustrates the heat transfer energy and temperature equalization. The symbol for heat is Q and the SI unit of energy is joule (newton meter), Other common units are the British thermal unit (Btu) and the calorie (Cal) [5, 7].

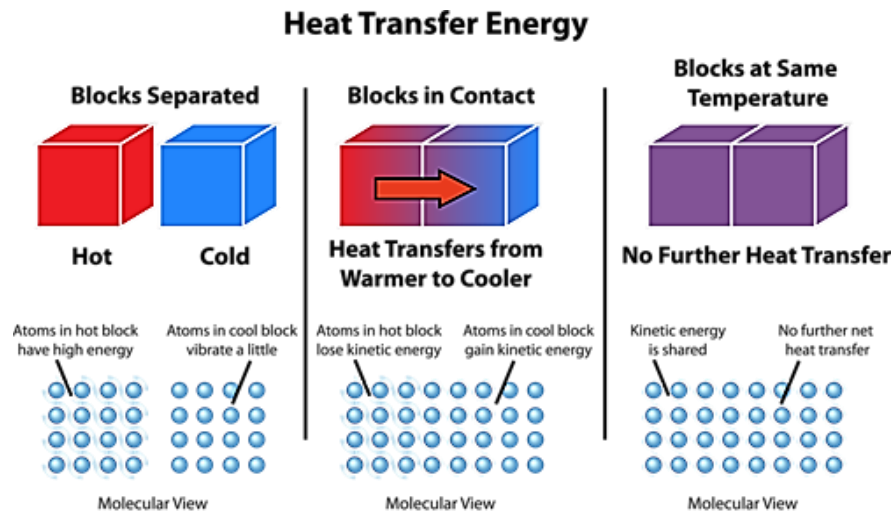


Figure I. 1. Heat transfer energy [8].

c. Heat flux: is defined as the rate at which the heat is being transferred by time and the surface area [5, 6].

$$q'' = \frac{\Delta Q}{A \Delta t} \quad \text{I.1}$$

q'' : Heat flux (measured in watts per square meter, W/m^2).

ΔQ : Amount of heat transferred (measured in joules, J).

A : Surface area through which heat is transferred (measured in square meters, m^2).

Δt : Time duration during which heat transfer occurs (measured in seconds, s).

After addressing the fundamental thermal quantities temperature, heat, and heat flux, it is important now to investigate the overarching concept that relates them together: heat transfer.

d. Heat transfer: is a scientific discipline concerned with the prediction and analysis of energy exchange between material bodies that occurs due to a temperature difference. While the field of thermodynamics defines this form of energy exchange as heat, it primarily addresses the quantity of energy transferred and the equilibrium states associated with such processes. [9]

Heat transfer extends beyond the thermodynamic description by focusing on the mechanisms and rates at which thermal energy is transmitted under specified conditions.

This includes the study of various modes of transfer namely, conduction, convection, and radiation, and the factors influencing these processes. The central distinction lies in the objective: whereas thermodynamics is concerned with the amount of heat exchanged, heat transfer seeks to quantify the rate at which this exchange occurs, thus providing a dynamic understanding of thermal interactions. [7, 9]

I.2.1 Heat transfer modes

We distinct three heat transfer modes among them:

I.2.1.1 Conduction

Conduction is a heat transfer mode mainly concerning solids. It involves heat transfer via the interaction of the molecules of that material. According to the second law of thermodynamics, which dictate the natural heat flow when a temperature gradient exists. The rate at which heat is transferred by conduction q_x is proportional to the temperature gradient $\frac{dT}{dx}$ times the surface area.

For heat conduction in one-dimensional, steady-state and through a homogeneous medium is:

$$q_x = -kA \frac{dT}{dx} \quad \text{I.2}$$

q_x = heat transfer rate (W)

$\frac{dT}{dx}$ = temperature gradient in in x-direction (K/m).

k = thermal conductivity (W/m·K).

A : cross-sectional area perpendicular to heat flow (m²).

k is positive constant and the minus sign is inserted so the second principle of thermodynamics is satisfied. The equation (II.2) is known as Fourier's law of heat conduction, after the French physicist Joseph Fourier. [5, 7, 9]

I.2.1.2 Convection

Convection is the transfer of heat through fluids, it consists of two mechanisms operating simultaneously. The first is heat transferred due microscopic molecular motion, which resembles conduction, the second is heat transferred through macroscopic motion of

the fluid of hotter regions to a cooler region due to a density gradient as shown in Figure I. 2. [5, 7]

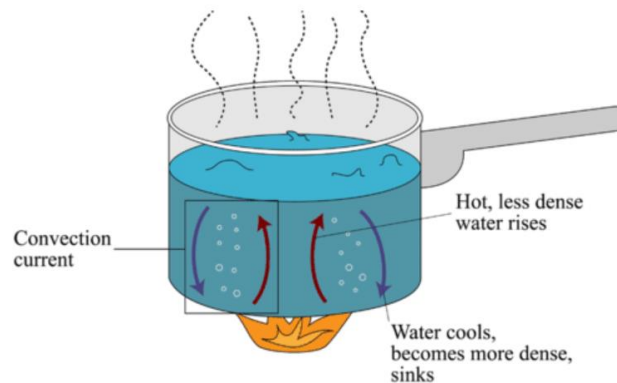


Figure I. 2. Convection heat transfer.

To express the overall effect of convection, we use Newton's law:

$$q = h A (T_s - T_\infty) \quad \mathbf{I.3}$$

q : heat-transfer rate (W).

h : convection heat transfer coefficient (W/m²·K).

A : surface area (m²).

h : convection heat transfer coefficient (W/m²·K).

T_s : Surface temperature (K).

T_∞ : Temperature of the fluid far from the surface (K).

I.2.1.3 Radiation

Radiation is the transfer of heat through electromagnetic waves, which occurs due to a body's temperature. Most of this energy is emitted in the infrared region of the electromagnetic spectrum, though some also can be visible. The term "thermal radiation" is used to differentiate it from other types of electromagnetic waves like radio waves, X-rays, or gamma rays. This type of heat transfer does not require a medium like fluid or solid material to occur. Any object with a temperature above absolute zero emits thermal radiation [5].

The amount of energy emitted from a surface as radiant heat depends on both its absolute temperature and its surface properties. An ideal emitter, known as a blackbody, radiates energy from its surface at a rate described by the following relationship:

$$q_r = \sigma A T^4 \quad \text{I.4}$$

q_r : thermal radiation heat transfer rate (W).

σ : Stefan–Boltzmann constant with a value of 5.67×10^{-8} (W/m²·K⁴). [13]

A : surface area of the radiating body (m²).

T : absolute temperature of the surface (K).

I.3 Energy storage

As the world advances toward alternative energy sources, driven by the inevitable depletion of fossil energy, we see a growing focus on ensuring a better sustainable energy use in the future [10]. One of the ways of achieving sustainability is the incorporation renewable energy sources, however these sources such as wind or solar are intermittent and transient in nature and depending on weather condition.

As a result, energy storage is one of the most efficient solutions, as it is capable of capturing excess energy produced during times of high generation and releasing it during periods of low production. This helps maintain a stable and reliable energy supply, reduces dependence on fossil fuels. [4]

I.3.1 Energy storage modes

Energy can be stored in various systems including mechanical, electrochemical, chemical, and thermal.

I.3.2 Mechanical (MES)

Mechanical energy storage is defined as the direct storage of kinetic or potential energy. Several systems were developed, among them is pumped hydro energy storage system, compressed air energy storage, and flywheel energy storage. The first two respectively are relying on potential energy conversion, while the last depend on kinetic energy [4].

I.3.3 Electrochemical (ECES):

Electrochemical energy storage is one of the most common energy storage systems used in today's world, the prime advantage for using the electrochemical storage systems is lightweight and compact especially in the field of electronics. It undergoes primarily of three major processes. First process is ionization, second is transport of charged particles (ion or electrons), and in the final stage is the recombining of charge completing the electrochemical reaction. This system is divided into two categories battery energy storage and flow battery energy storage. The emergence of batteries was in the 18th century, from the work of the Italian scientist Alessandro Volta, known as the voltaic pile. This invention was a pivotal point in energy storage [3, 4, 10].

I.3.4 Chemical (CES)

While ECES and the CES systems are based on the same principal i.e., storing energy within the chemical bonds between atoms and molecules of the materials. The key difference is how that energy is released and utilized. ECES converts chemical energy into electricity through reversible reactions within a device such as a battery. CES, on the other hand focuses on converting that chemical energy into mechanical to release heat or work. This type of energy storage plays a dominant role in the global electricity generation, transportation and industry. These chemical fuels include a various type of substances such as coal, diesel fuels, LPG, propane, ethanol, and hydrogen [3, 10].

I.3.5. Thermal (TES)

Thermal energy storage (TES) refers to the effective storage of thermal energy in a material, in other words it is the temporary storage of thermal energy for instance solar thermal energy or geothermal energy for later use. It undergoes through several processes such as melting, condensing, or vaporization [10, 11].

Three main TES mechanism can be distinct: thermo chemical storage (TCS), sensible heat storage (SHS), and (LHS) latent heat storage (figure I. 3).

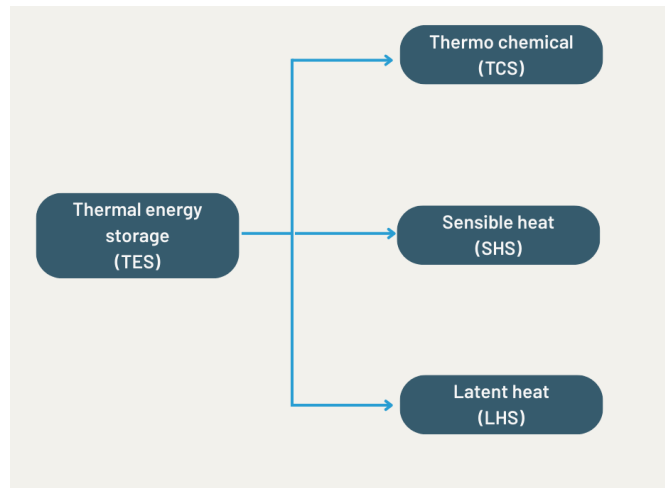


Figure I. 3. TES storage mechanism [12].

Most mechanisms store thermal energy at a broad temperature interval. This type of energy storage has a wide range of applications, from industrial cooling at temperature below $-18\text{ }^{\circ}\text{C}$ to high temperature industrial heat storage exceeding $175\text{ }^{\circ}\text{C}$. or residential and commercial temperature control (heating and cooling). Chemical energy storage has limited practical applications, as several technical and economic challenges remain unresolved. To date, research in the field of thermal energy storage has primarily focused on sensible heat and latent heat storage systems [4, 13].

I.4 Thermal energy storage (TES) mechanism

I.4.1 Thermo chemical (TSC)

TCS relies on the absorption and release of heat during chemical reactions; it can be categorized as exothermic reaction and endothermic. TCS has a higher thermal capacity; it can store thermal energy from 0°C to 900°C and for a period of time up to a month [12].

Endothermic reaction (Charging): $AB + \text{heat} \rightarrow A + B$ **I.5**

Exothermic reaction (Discharging): $A + B \rightarrow AB + \text{heat}$ **I.6**

I.4.2 Sensible heat (SHS)

SHS is the ability to store or extract thermal energy in a material (solid or liquid) by increasing or decreasing its temperature, in which does not change its phase during the process. In this type of storage large amounts of heat storage materials are required, and energy temperature can reach up to $2400\text{ }^{\circ}\text{C}$ [4, 12]. The heat capacity of a sensible storage system can be calculated through the following equation:

$$Q_{sensible} = \int_{T_i}^{T_f} mc_p dT = mc_p(T_f - T_i) \quad (\text{I.7})$$

$Q_{sensible}$: storage capacity (J).

T_f : final temperature (K).

T_i : initial temperature (K).

m : the mass of storage material (kg).

c_p : the specific heat capacity ($\text{J}\cdot\text{kg}^{-1}\cdot\text{K}^{-1}$).

Based on eq (I.7), the high specific capacity c_p can have an impact on the amount of the thermal energy stored [11, 14, 15].

I.4.3 Latent heat (LHS)

LHS refers to the energy absorbed or released when a storage material undergoes a phase change. The ability of the storage material to undergo this phase change at a consistent temperature is a crucial factor affecting the performance of LHS systems [4, 12]. In order to achieve this, we require a material capable of changing its phase in a suitable temperature interval. The reasoning for this is when the material is heated, its sensible heat increases until it reaches the melting point, from the initiation to the completion of melting the material stores a significant amount of heat in the form of latent heat. For a given volume, the latent heat storage is significantly higher than sensible heat as the latent heat provides substantially high energy storage temperature and maintains a practical difference. In engineering terms this material is known as a phase change material or PCM. [14, 15, 16]

I.5 Conclusion

Thermal energy storage stands as a pivotal solution to the intermittency of renewable energy sources. By leveraging fundamental thermal principles and advanced storage techniques such as SHS, LHS, and TCS, TES systems can efficiently balance energy supply and demand. These mechanisms offer versatile applications across industrial, commercial, and residential sectors.

Chapter II:

*Phase change materials:
fundamentals and research trends*

II.1. Introduction

Research on TES and on PCMs in particular, has been a major field of investigation for the last decades [18]. The reason for this is the potential to improve energy efficiency and achieving sustainability [4]. To understand the emergence of PCMs, it is noted that their first discovery dates back to the early 1900s in the work of Alan Tower Waterman of Yale University while studying thermionic emission of certain hot salts. He found that the conductivity of the chalcogenide can be altered progressively, this draws the attention of researchers and developers [19]. Figure.II.1 represents the development of PCMs through time.

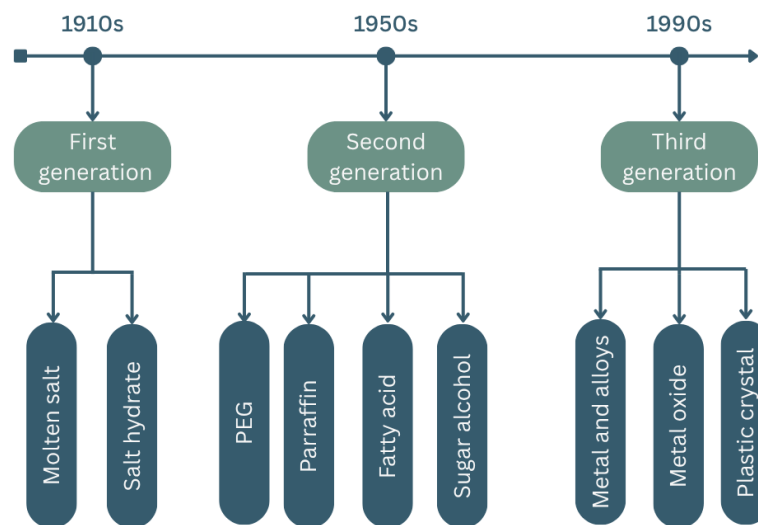


Figure.II.1. The development of PCMs through time [20].

II.2. Definition

Phase change materials or PCMs are a unique class of materials capable of capturing and storing a large quantity of thermal energy during phase transition, what made them unique is the ability to store a significant amount of heat in a narrow temperature range. To illustrate, initially the temperature of PCM in its solid-state increases as it absorbs heat (sensible heat). However, once the PCM reaches the phase transition temperature, it begins to absorb an enormous amount of heat (latent heat) at a nearly constant temperature [14, 21] as shown in Figure.II.2.

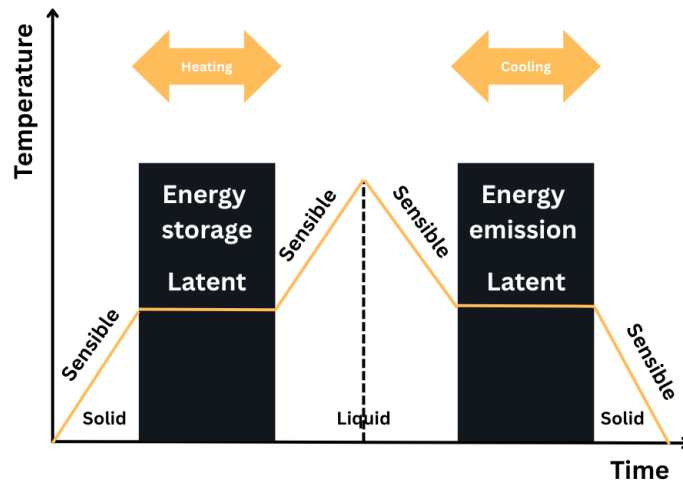


Figure.II.2. Heat storage mechanism in a PCM [22].

The phase change process could change the state between solid and liquid by melting or freezing, known as solid–liquid PCMs or change between liquid and gas through condensation and vaporization, called liquid–gas PCMs or change the phase between two solid states, known as solid–solid PCMs (fig.II.3). Therefore, solid–gas transitions store the highest amount of energy, while the solid–solid phase change has a quite low latent heat transfer [20].

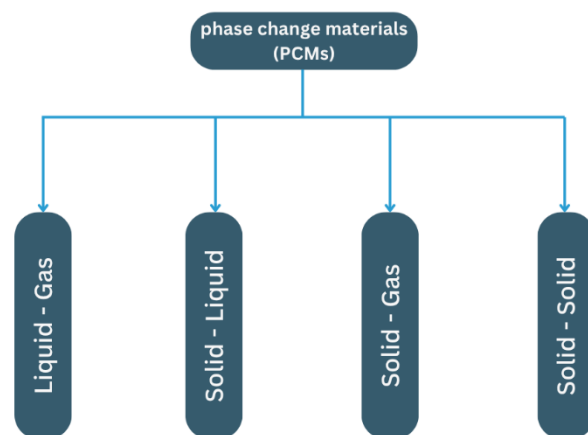


Figure.II.3. The phase states of PCMs.

II.3. Types of phase change materials

PCMs can be classified based on several factors, the most basic function of a PCM is described by the enthalpy $h(T)$, more specifically the phase change enthalpy $\Delta_{pc}h$ and the phase change temperature T_{pc} ; in other words, the melting temperature and latent heat of fusion [15, 23]. Those are the primary selection properties of a PCM for practical application, since none of the material that exists has all the properties required for an ideal system, one has to develop an adequate system to solve the problem. For example, increasing thermal conductivity by introducing metallic fins to the system, or preventing

supercooling by present a nucleating agent [27]. PCMs are subdivided into three types including organic, inorganic, and eutectic PCMs combining organic and inorganic. Based on various studies [13, 16, 18, 20], the figure below summarizes the most important criteria that govern the selection of PCMs (it will be discussed in details in section II.4.).

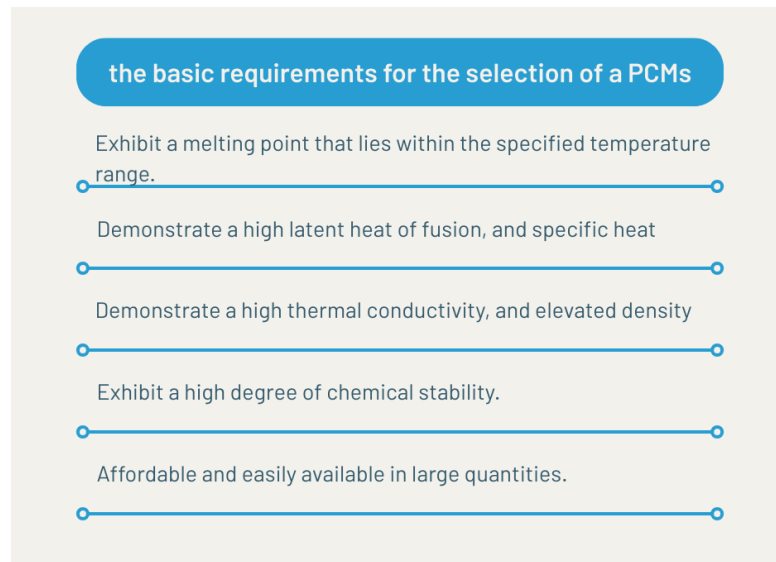


Figure.II.4. Criteria for PCMs selection [13, 16, 18, 20].

PCMs are commonly classified into different types based on specific criteria. In the following section, we discuss these types.

II.3.1. Organic phase change materials

Organic PCMs are categorized into paraffins compounds and non-paraffins compounds (fig.II.5), represent one of the most widely utilized types in applications today mainly for their safe non-reactive materials. Paraffin-based PCMs are in particular is one of the most preferred types in TES systems. Where they may be employed individually or in combination to achieve a desired temperature range.

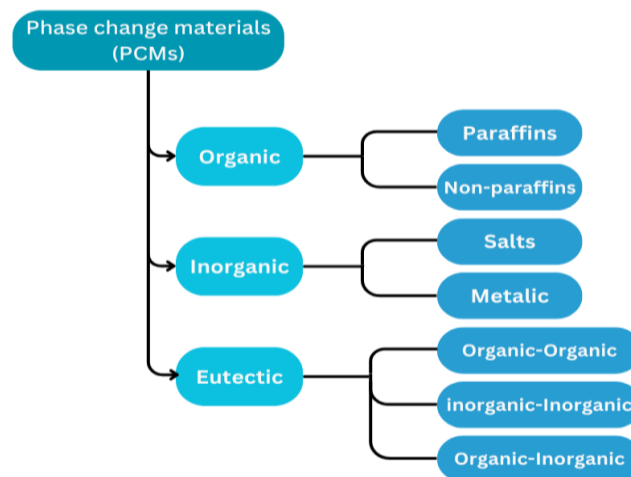


Figure.II.5. Families of phase change materials [25].

Non-paraffin organic PCMs are derived from a broad range of organic, including esters, fatty acids, glycols, and alcohols. Among these, fatty acids have gained a significant attention due to their numerous advantages. These include cost-effectiveness, the elimination the need for additional encapsulation and their overall suitability for practical applications [14,16]. The major limitation of these type of materials is the low thermal conductivity and flammability [16]. Table II.1 represents the main advantages and disadvantages of organic PCMs.

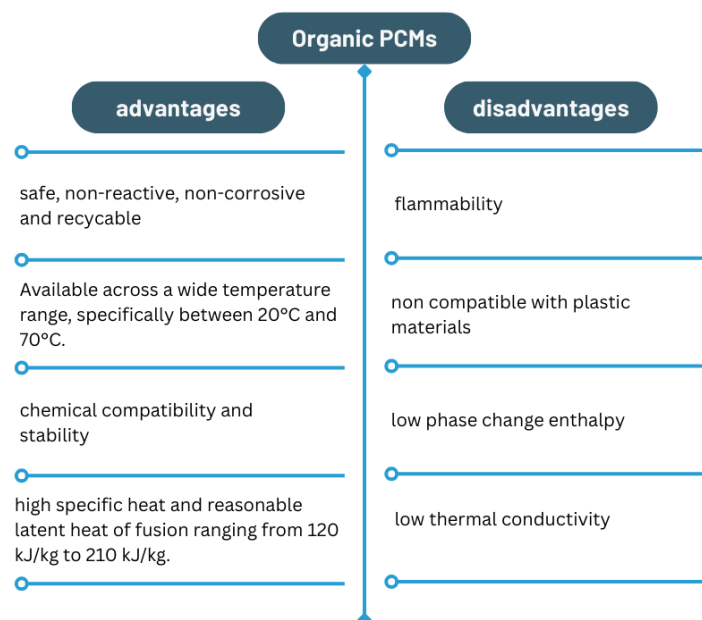


Table II.1: Advantages and disadvantages of organic PCMs [16.26]

II.3.2. Inorganic phase change materials

Unlike organic PCMs, the prime advantage of inorganic PCMs is they are not flammable and much cheaper. These PCMs are grouped in subclasses, namely, metals and salts. More specifically metal alloy, metal compound and salt hydrates [14]. Salt hydrates often exhibit a tendency to segregate during thermal cycling due to incongruent melting. This last can lead to thermal stratification which can be solved by simply adding excess water [16].

Metals can either consist of metals alloy with low melting point temperatures or metal compound. A significant advantage of metal PCMs is their high thermal conductivity. Which will increase the heat transfer rate. Nevertheless, its low latent heat of fusion per unit weight presents a significant obstacle. Typical example of metal PCMs is Gallium Ga_{31} (fig.II.6) with melting point of 29.76 °C [27]. The advantages and disadvantages of inorganic PCMs are presented in table II.2.



Figure.II.6. Gallium [27].

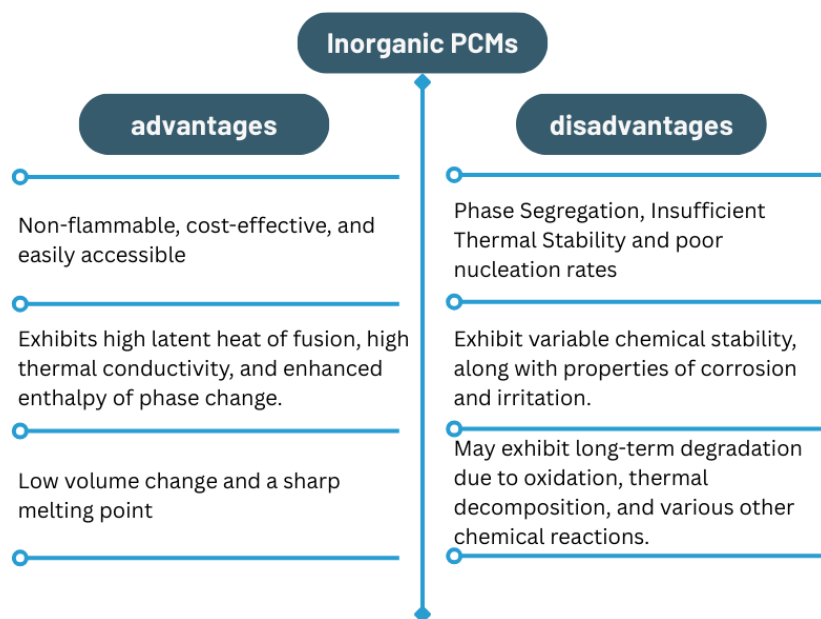


Table II.2. Advantages and disadvantages of inorganic PCMs [24, 26].

II.3.3. Eutectic phase change materials

Eutectic PCMs on the other hand, consist of two or more components, which can include combinations of organic-organic, inorganic-inorganic, or inorganic-organic materials. Among them, two types are broadly used: Organic-Organic PCMs and Organic-Inorganic PCMs.

Various compounding techniques can be employed to meet specific practical requirements. To create organic complex phase change materials that achieve the desired melting point and latent heat storage for practical needs, a common approach involves blending two or more organic PCMs by melting and mixing them at different phase change temperatures [14]. Eutectics PCMs have sharp melting point similar to pure substance with volumetric storage density that is slightly higher than organic compounds. However, limited data are available on their thermo-physical properties as the use of these materials is very new to thermal storage applications [24].

II.4. Thermo-physics properties of phase change materials

It was mentioned in previous section, that the most basic functions of a PCMs are the melting point and the latent heat of fusion, yet there are several properties subdivided into four subclasses namely:

a. Thermal properties:

A PCM should exhibit :

- A melting point that lies within the specified temperature range depending on the desired application.
- A high latent heat of fusion per unit mass, to store a significant amount of heat.
- Elevated specific heat to provide additional heat absorption and release [13, 14].
- A high thermal conductivity.

b. Physical properties:

A PCM should have:

- A high-density level to reduce the size of the container.
- No supercooling due to the solidification of the PCM below freezing temperature.

- Low vapor pressure to reduce flammability and containment problems.
- Long-term stability for recycling purposes [13, 16, 18].

c. Chemical properties:

Having a:

- High chemical stability of a PCM is a must-have property, the reason for this is that multiple melting and freezing cycles are imposed on the PCM, potentially causing a change in the composition, which can lead to performance degradation.
- No level of corrosiveness or incompatibility with the container material, thus affecting the life-span of the latent heat storage systems [13, 16].
- Non-poisonous and non-explosive PCM is important to ensure environmental safety.

d. Economical properties: PCMs are selected for their advantageous economic properties, particularly their availability and low cost.

II.5. Applications of phase change materials

PCMs are utilized in wide range of sectors depending on the required temperature, from domestic freezing to electricity generation. Figure.II.7 helps to further understand the specified temperature based on the desired application [28].

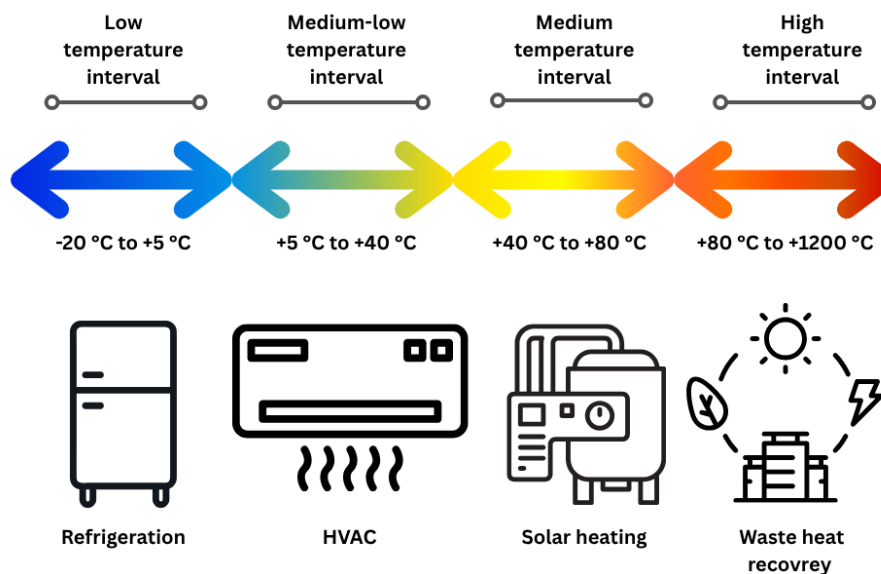


Figure.II.7. Specified temperature based on the desired application [14, 22].

II.5.1. Building and construction

In order to achieve sustainability, implementing PCMs in building and construction is essential to maintain thermal efficiency. To this end, PCMs are incorporated in building

structures, such as walls, floors, and roofs. This last enhances thermal comfort both in residential and commercial temperature control. In addition, it contributes to reducing auxiliary needs for heating and cooling [14, 22].

Several technologies have been developed in order to better integrate PCMs into building materials, namely the impregnation of PCM by immersion or imbibing and encapsulation of PCM whether it is macro or micro/nano encapsulation [29].

II.5.2. Electronic and thermal management

Phase change materials (PCMs) have emerged as a pivotal innovation in the thermal management of electronic devices, providing an advanced and efficient method for dissipating waste heat generated during operation. Their use extends across a broad spectrum of applications, including consumer electronics such as smartphones and laptops, as well as more demanding environments like data centres and industrial power electronics [17, 30].

II.5.3. HVAC systems and industrial processes

For heating, ventilation, and air conditioning (HVAC) systems, PCMs can be used in walls or ceiling to absorb heat during the day and release it at night reducing the needs for constant air conditioning thus reducing peak loads. They can also be used in industrial sectors including passive cooling processes of photovoltaic panels (PV), pharmacy and medicine applications and transportation cold food or medicine [22, 28].

II.6. Challenges in phase change material technologies and their solutions

As we established in previous sections, PCMs is selected based on their thermophysical, kinetic and chemical characteristics. However, some of the challenges require the development of an adequate solution. As these properties present a major challenge to a PCM systems namely:

- a. **Phase segregation:** certain PCMs such as salt hydrate tend to melt incongruently which leads to changes in chemical composition and a decrease in the high storage density with several operational cycles. Thus, leads to a phase separation (segregation) affecting the heat transfer efficiency rates [15, 16, 31].
- b. **Low thermal conductivity:** poor thermal conductivity is major concern for organic PCMs in general and paraffins in particular, this characteristic affects the material's ability to efficiently absorb and release heat, thereby slowing both the charging and discharging

processes in thermal energy storage (TES) systems. To address this challenge, various enhancement techniques are employed most notably, the incorporation of thermally conductive additives or encapsulation methods. Typically, organic PCMs exhibit thermal conductivities around $0.2 \text{ W/m}\cdot\text{K}$, significantly lower than those of inorganic PCMs, which average about $1 \text{ W/m}\cdot\text{K}$. This difference becomes especially critical during the solidification phase [18, 31].

- c. **Subcooling:** from kinetic perspective subcooling or supercooling is another crucial problem affecting the efficiency of inorganic PCMs. This phenomenon occurs when the phase transition does not occur at the material's typical melting point, but only after it has been cooled to a temperature several degrees lower. Such a delay in the energy release process reduces the responsiveness of thermal energy storage (TES) systems and compromises their effectiveness. This delay is referred to as the degree of subcooling, and it can significantly reduce heat recovery performance. This issue was fixed by introducing nucleating agent to help lessening subcooling and initiating the phase change process more consistently at the desired temperature [15, 31].
- d. **Effect of corrosion:** from a chemical perspective, another critical factor affecting PCMs, particularly salt hydrates, is their potential to cause corrosion of metal containers. Salt hydrates are notably more corrosive due to their ionic nature. Corrosion occurs when metal ions interact with the PCM, which acts as an electrolyte, facilitating electrochemical reactions with the container metal. This type of degradation can manifest across various combinations of metals and ionic contaminants.

Given this risk, ensuring chemical compatibility between the PCM and the storage container material is essential for system longevity and performance. To mitigate corrosion, corrosion inhibitors are widely used. These inhibitors fall into two main categories: oxide films and chemical additives. Additives are typically applied as protective surface coatings that act as physical barriers, preventing direct contact between the metal and the corrosive medium, thereby extending the service life of TES systems [18, 31].

- e. **Long term stability:** A PCM is considered stable if its thermophysical and chemical properties are unaffected by repeated charging and discharging cycles. Stability is a key criterion in determining the long-term reliability and performance of a phase change material in thermal energy storage (TES) applications. This includes maintaining its phase transition temperature, latent heat of fusion, thermal conductivity, and chemical composition across hundreds or even thousands of cycles. Degradation in stability can

result in reduced energy storage capacity, phase segregation, or the formation of by-products that compromise system efficiency [18, 31].

Researchers and developers have proposed over the last decade various solutions to address these challenges with several methods. Table II.3 represents some of the enhancement methods proposed to address the challenges.

Challenge	Enhancement method	Description
Low thermal conductivity	Conductive additives	Improves heat transfer by adding materials with high thermal conductivity.
	Encapsulation	Enhances thermal response and prevents leakage.
	Finned surfaces	Increases contact area for heat transfer.
Subcooling	Nucleating agents	Initiates crystallization near the melting point to reduce subcooling.
	Surface modification	Textured surfaces can promote nucleation and reduce subcooling
Corrosion	Corrosion inhibitors	Prevent electrochemical reactions between PCM and container metal
	Protective coatings	Applied to metal surfaces to block interaction with corrosive PCMs
	Material compatibility selection	Choosing container materials that resist corrosion with given PCM
Stability (Thermal/Chemical)	Stabilizing additives	Prevents phase separation (segregation) or decomposition
	Thermal cycling tests	Identifies suitable PCMs through accelerated aging

Table II.3: Enhancement methods for PCM systems.

II.7. Bibliographic research

The present section focuses on various studies that integrate PCMs into different thermal energy storage systems (TESS), focusing on the enhancement techniques employed in each case.

1. N. Stathopoulos, and al (2016), [32] the study introduces a PCM-Air heat exchanger designed (fig.II.8) to reduce peak energy demand while improving thermal comfort and indoor air quality.



Figure.II.8. The Air-PCM exchanger during fabrication.

It uses paraffin plates integrated into a ventilation system and employs both experimental and numerical modelling via the apparent heat capacity approach and finite difference methods. Validation was achieved by comparing simulation results with real-world data, and a preliminary control strategy was proposed.

Key Contributions:

- PCM integration in air ventilation systems.
- Peak load management strategy development.

2. Y. Allouche and al (2015), [33] experimental study focuses on comparing the thermal energy storage capacity of microencapsulated PCMs (45% w/w concentration) with sensible heat storage unit using water in a horizontal tank. The experimental study reveals a 53% improvement in energy storage using PCMs over water.

Key Contributions:

- Enhanced energy storage capacity compared to conventional water systems.
- Improved heat transfer dynamics during phase change.

3. V. Safari and al (2021), [34] experimental-numerical study explores the impact of fin design (fig.II.9) and tube positioning on PCM melting behaviour in heat exchangers. Bifurcated fins and eccentric tube positions were made to significantly enhance melting rates and heat transfer efficiency.

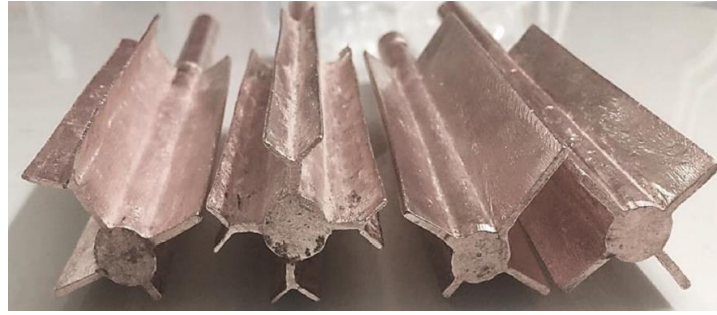


Figure.II.9. Photographs of the straight and bifurcated finned tubes.

Key Contributions:

- Innovative bifurcated fin design for heat transfer enhancement.
- A significant 85% decrease in melting time was obtained by eccentric tube heat exchanger with a long upper bifurcated fin and a short lower straight fin.

4. Y. Xu and al (2021), [35] this study investigates how porous media and eccentric geometry affect melting performance in a shell-and-tube LHTES unit using PCM based on the fixed-grid numerical method. The authors derive predictive correlations based on a modified Rayleigh number that reflects flow resistance from porous materials. The combination of optimized eccentricity and porous medium can reduce melting time by up to 43.1%.

Key Contributions:

- Established analytical correlations for optimum eccentricity and melting time.
- Demonstrated that integrating porous media with eccentricity outperforms using either alone.
- The combination of optimized eccentricity and porous medium can reduce melting time by up to 43.1%.

5. J Yang and al (Paper 2016), [36] This study presents an experimental investigation into the performance of a shell-and-tube latent heat thermal energy storage system enhanced with composite PCMs. Paraffin wax was used as the base PCM, with enhancements via copper foam and a bottom fin to overcome its low thermal conductivity (fig.II.10).

Key Contributions:

- Incorporating copper foam accelerates the melting process by over 33% with significant improvement in heat transfer.
- Found HTF temperature to be more influential than flow rate on system performance.

- Provided a comparative performance analysis of pure PCM, PCM with copper foam, and PCM with foam and fin (fig.II.11).

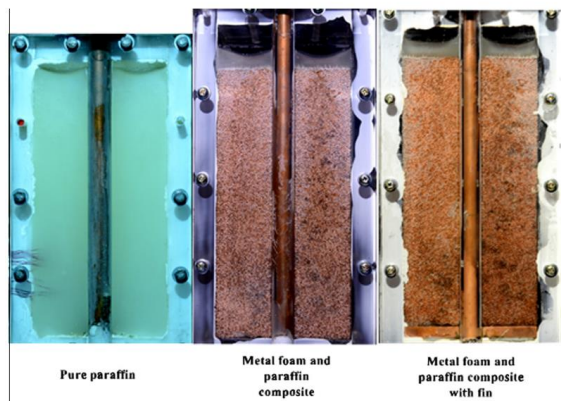


Figure.II.10. Test sections.

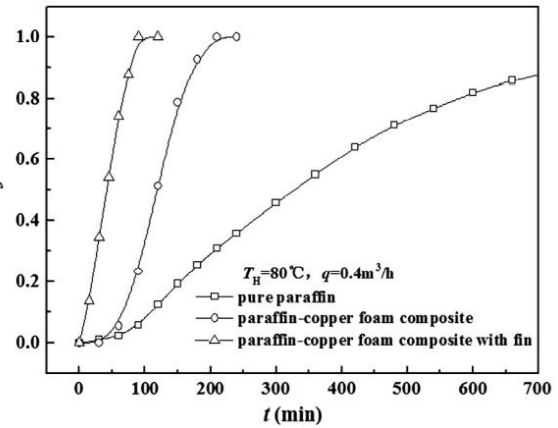


Fig. 16. Variations of liquid fraction with time for different samples.

Figure.II.11. Variation of liquid fraction with time for different samples

II.8. conclusion

We have seen in this chapter an overview of phase change materials, from their different types with details for each type to the technological challenges they present, and some of the enhancement methods proposed to address these challenges. We conclude this chapter by introducing some recent studies that integrate PCMs into different thermal energy storage systems (TESS).

Chapter III:

*Mathematical formulation and
numerical modeling*

III.1. Introduction

As we established in previous chapters the principals of heat transfer, energy storage and the fundamental properties, classifications, and applications of phase-change materials, alongside an overview of current research trends and challenges. Building upon this, chapter focuses on the mathematical formulations and numerical modelling techniques employed to simulate and analyses PCM behavior. This work is focused on the effect of eccentricity in annular system and the study of the thermal behavior of organic PCM using enthalpy porosity method. Based on the enthalpy-porosity method, two-dimensional model is performed and solved by Ansys Fluent to simulate and analyses the thermal behavior of the PCM. This allowed for detailed investigation into heat transfer mechanisms and performance optimization under various operating conditions.

III.2. Physical model

The cross-section of a two-dimensional geometry of an annular thermal energy storage system with eccentricity is shown in figure III.1(a). The PCM occupies the annular space between the inner and outer tubes. The diameters of the inner and outer tubes are denoted as D_i with 20 mm and D_o with 40 mm, respectively (fig.III.1b). The PCM is initially in solid state at 303 K in temperature. A hot temperature of 353 K is subjected to the inner tube while keeping the outer cylinder tube thermally adiabatic.

For this study, we distinct three cases. The first one is concentric circle, the second and the third are eccentric circles. The distances l_1 , l_2 , and l_3 are 10 mm, 6 mm, and 3.3 mm, respectively, and represent the vertical distance between the bottom point of the inner tube and the approximate bottom point of the outer tube under different eccentric configurations (fig.III.1b).

It may be noted that the fluid flow and heat transfer are symmetrical with respect to the vertical axis of the annular system, the computational domain of the symmetric models are shown in figure. III.1(b).

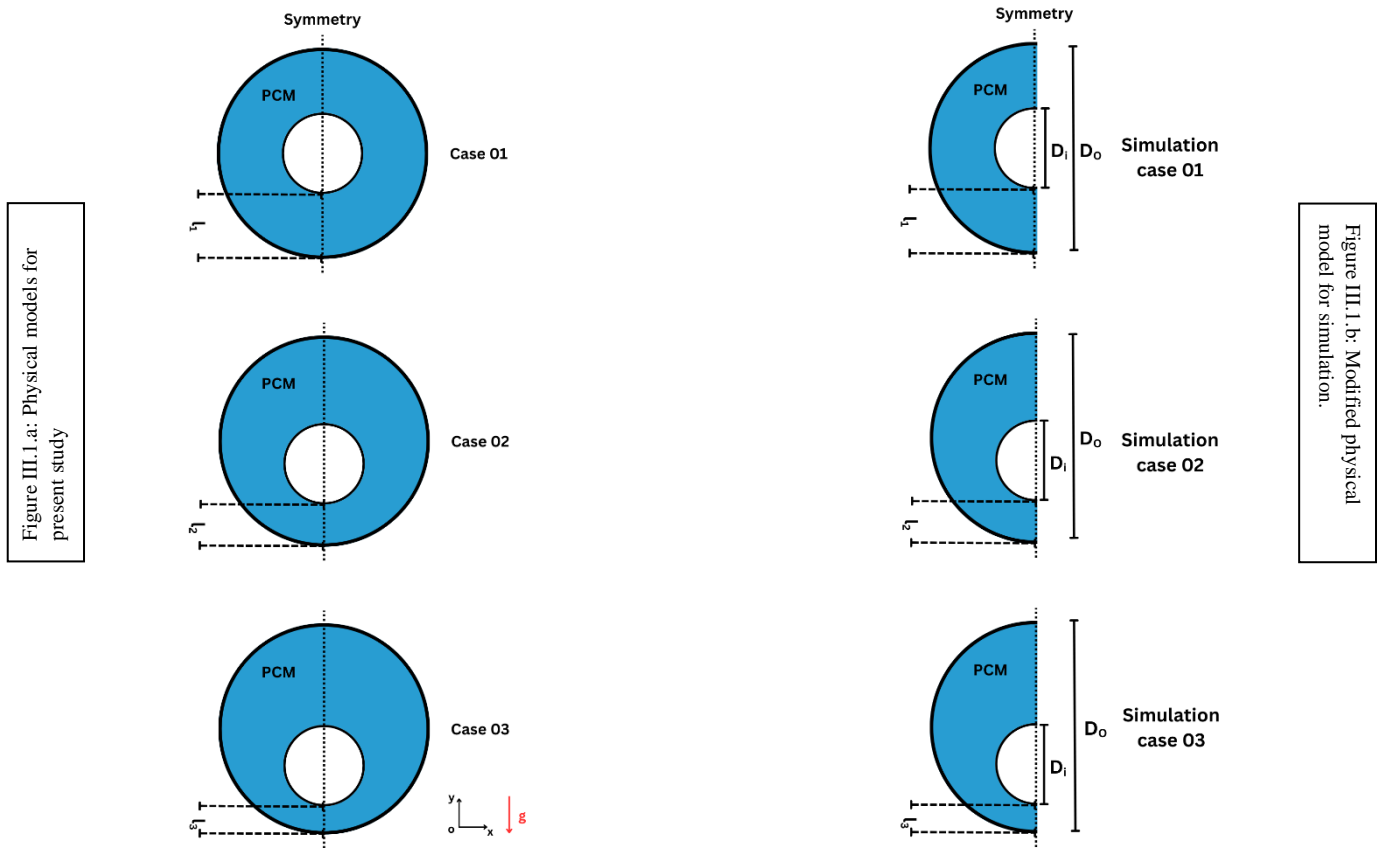


Figure III.1. a: Physical models for present study

Figure III.1. b: Modified physical model for simulation.

III.3. Thermophysical properties

Stearic acid is used as phase change material in this study with thermo-physical properties at solid and liquid states, listed in table III.1 [37].

Property	Symbol	Value	Unit
Solidus temperature	T_s	327.5	K
Liquidus temperature	T_l	337.1	K
Density (solid)	ρ	1150	kg/m^3
Density (liquid)	ρ_l	1008	kg/m^3
Specific heat capacity (solid)	$C_{p s}$	2830	$\text{J}/(\text{kg}\cdot\text{K})$
Specific heat capacity (liquid)	$C_{p l}$	2380	$\text{J}/(\text{kg}\cdot\text{K})$
Latent heat of fusion	H_{sl}	186.5	kJ/kg
Thermal conductivity	K	0.29	$\text{W}/(\text{m}\cdot\text{K})$
Dynamic viscosity	M	0.0078	$\text{Pa}\cdot\text{s}$
Thermal expansion coefficient	B	0.00081	$1/\text{K}$

Table III.1. Thermophysical properties of stearic acid [37]

III.4. Problem formulation

How to track the solid liquid interface is the main challenge in this study. In order to investigate phase change problem. Enthalpy-porosity method was employed to simulate and calculate the liquid fraction of the PCM. As shown in Fig.III.1. b, the simulation cases in this study. Figure.III.2 gives the details of the grid system. Structured mesh was used in all cases with finer grids near the hot inner wall to capture the variation in all parameters.

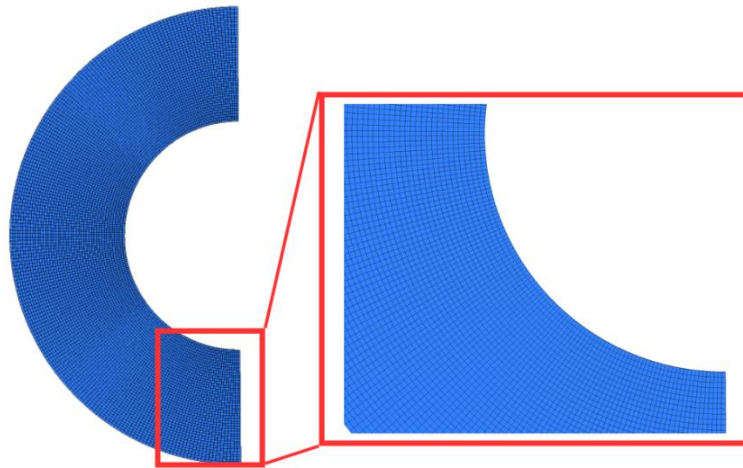


Figure III.2. Schematic of grid system (Case 01).

Assumptions and simplification: The melting process of a phase change material is a complex phenomenon, characterized by non-linear and unsteady behaviour. To simplify the numerical solution, PCM is assumed to be homogeneous, incompressible, Newtonian fluid flowing in a laminar regime. The interface of the solid and liquid phase of PCM is defined by a thin mushy zone which is a mixture of solid and liquid phases. The buoyancy source term in the governing equations models the density variation effects through Boussinesq approximation. It allows the density to be treated as mean constant density in the governing equations. Consequently, volume change during the phase change process of PCM is neglected. Therefore, 2D, constant volume, enthalpy porosity numerical methodology is adopted to resolve the problem [37].

Governing equations: based on the previous assumption the general governing equations are expressed in the following:

1. Continuity Equation

$$\nabla \cdot u = 0 \quad \text{III.1}$$

This ensures the conservation of mass in an incompressible flow.

2. Momentum Equation

$$\rho \frac{\partial u}{\partial t} + \rho(\nabla u)u = -\nabla p + \mu \nabla^2 u + \rho g + s \quad \text{III.2}$$

Where:

ρ : Density.

μ : Dynamic viscosity.

u : Velocity vector.

p : Pressure.

g : Gravitational acceleration.

S : Source term representing phase change effects.

3. Energy Equation

$$\frac{\partial}{\partial t}(\rho H) + \nabla \cdot (\rho u H) = \nabla \cdot (k \nabla T) \quad \text{III.3}$$

Where:

H : Total enthalpy.

k : Thermal conductivity.

T : Temperature.

4. Enthalpy components

Total enthalpy H includes

- Sensible heat enthalpy (h)
- Latent heat (ΔH)

$$h = h_{ref} + \int_{T_{ref}}^T cp \, dT \quad \text{III.4}$$

$$\Delta H = \phi L \quad \text{III.5}$$

$$H = h + \Delta H \quad \text{III.6}$$

Where:

cp : Specific heat at constant pressure

L : Latent heat of fusion

ϕ : Liquid fraction

h_{ref}, T_{ref} : reference enthalpy and temperature respectively

5. Source term definition

The source term in the momentum equation due phase change is defined as:

$$S_x = -A(\phi)\mu \quad \text{III.7}$$

6. Liquid Fraction ϕ definition

$$\phi = \begin{cases} 0 & \text{if } T \leq T_{sol} \\ \frac{T-T_{sol}}{T_{liq}-T_{sol}} & \text{if } T_{sol} < T < T_{liq} \\ 1 & \text{if } T \geq T_{liq} \end{cases} \quad \text{III.8}$$

Where:

T_{sol} = solidus temperature.

T_{liq} = liquidus temperature.

7. Porosity function $A(\phi)$:

$$A(\phi) = \frac{C(1-\phi)^2}{\phi^3 + \epsilon} \quad \text{III.9}$$

Where:

C = empirical constant.

ϵ = small numerical constant to avoid division by zero.

III.4. Conclusion

In this chapter, we modelled the phase change phenomenon using ANSYS Fluent software, which employs the enthalpy-porosity approach, where the mushy zone is considered as a porous medium and the liquid fraction represents its porosity.

The results of the simulation of the present problem are discussed and interpreted in detail in the next chapter.

Chapter IV:

*Interpretation of the results and
discussion*

IV.1. Introduction:

This chapter presents the interpretation and discussion of the results obtained from the simulations of three different heat exchanger cases described in Chapter III. Each case involves studying how a phase change material (PCM) melts over time in different cylindrical heat exchanger configurations; one concentric and two eccentrics. By analysing temperature, liquid fraction, and velocity streamlines at various time intervals, we aim to understand how heat is transferred in each setup and what role natural convection and geometry (eccentricity effect) play in improving thermal performance. This interpretation helps identify which configuration is more effective in enhancing the melting process of the PCM.

IV.2. Results interpretation:

A. Case 01:

Figure IV.1 displays case 1 of the simulation results. A series of cross-sectional contours of concentric cylindrical heat exchangers depicting liquid fraction (a), velocity streamlines (b), and temperature (c) at several selected times (1, 2.5, 6, 7, 9, 11, 15, and 25 min).

At initial time, the PCM is in solid state with temperature equal to 303 K which is below the phase change temperature. When we imposed a hot temperature of 353 K on the inner tube, the solid PCM temperature increases by absorbing sensible heat until it reaches melting point. At the melting point, the PCM absorbs heat from the hot wall and begins to change its state from solid to liquid by using latent heat.

After 1 minute of melting (figure IV.1), we observe that the liquid fraction has a circular shape near the hot inner wall, with uniform variation in velocity streamlines and temperature, highlighting the dominant influence of conduction as the primary heat transfer mechanism through the melted phase of the PCM. As time elapsed (2.5 min), the melting front marks the appearance of a wavy shape at the upper space of the annulus. After 6–9 minutes, we notice that a significant portion of the PCM was melted, and the melting front extended to reach the upper surfaces of the inner tube. At this stage, the temperature contours become non-uniform and the streamlines appear a circular movement of the liquid PCM, this indicates the development of natural convection: the difference in the density of the melted PCM, resulting from the temperature gradient, leads to a buoyancy effect caused by the rising hot fluid, which

transports heat upward. This last substantially enhances the melting rate in the upper section compared to the lower section.

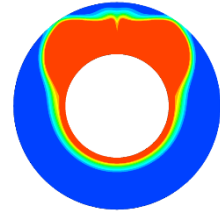
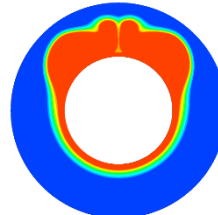
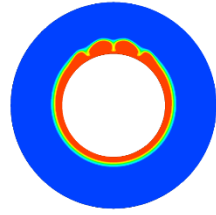
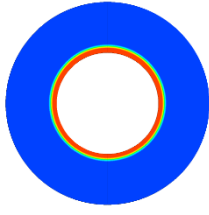
In the advanced stage of the melting process (approximately 11 to 25 minutes), the thermal behavior within the concentric cylindrical heat exchanger becomes more stable, with thermal stratification of the PCM at the lower part: the upper region of the PCM is entirely liquefied, the temperature contours become uniform again, and the melting rate slows down as a result of heat conduction dominating at the final stage. The entire PCM domain was melted after 42 minutes.

1 min

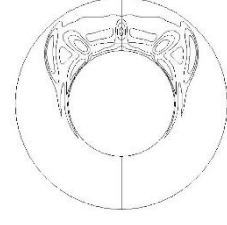
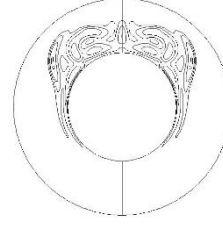
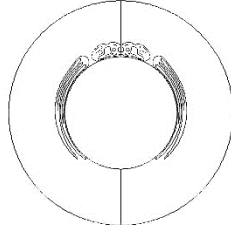
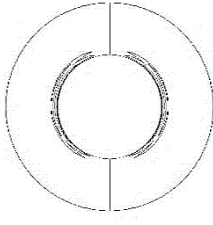
2.5 min

6 min

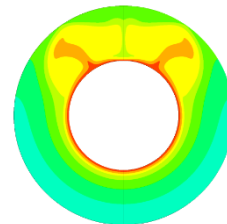
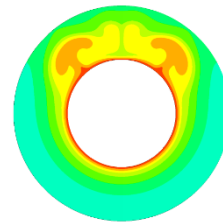
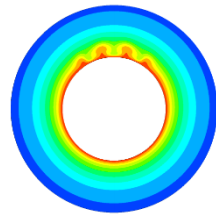
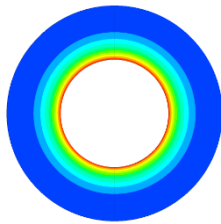
7 min



(a)



(b)



(c)

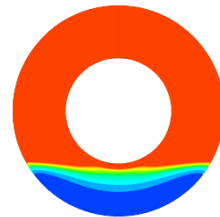
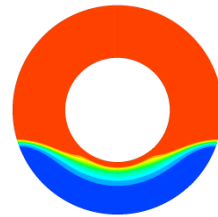
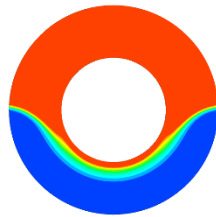
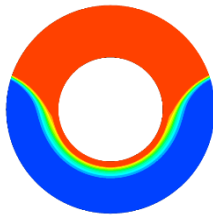
Case (01)

9 min

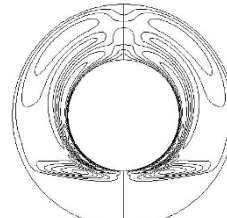
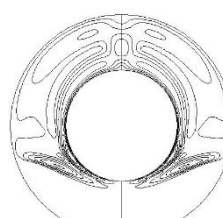
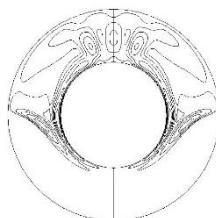
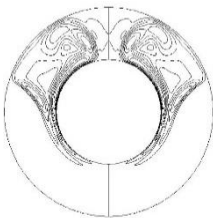
11 min

14 min

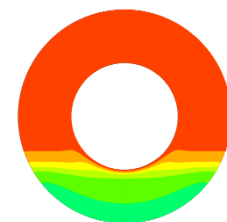
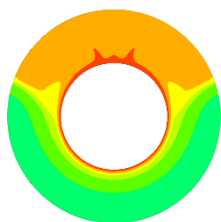
17 min



(a)



(b)



(c)

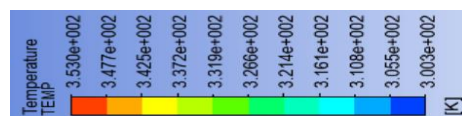
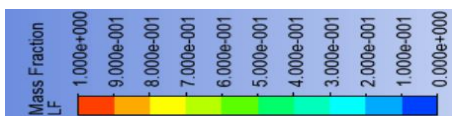


Figure IV. 1: results of simulation Case 01 (a) liquid fraction (b) streamlines (c) temperature

Figure IV. 2 and IV. 3 represent liquid fraction and PCM average temperature development through time respectively. We observe a significant increase in both liquid fraction and PCM average temperature at approximately the first 14 minutes due to the dominance of the buoyancy effect that accelerate the melting rate at upper space of the annulus, which confirm the results obtained in Figure IV. 1. After that and during the final two-thirds of the melting process, the parameters clearly indicate a change in the variation, with the rate of change gradually decreasing over time: at this stage thermal stratification at lower part of the annulus with the dominance of heat conduction result a decline in melting speed, matching what was observed in the results discussed in figure IV. 1.

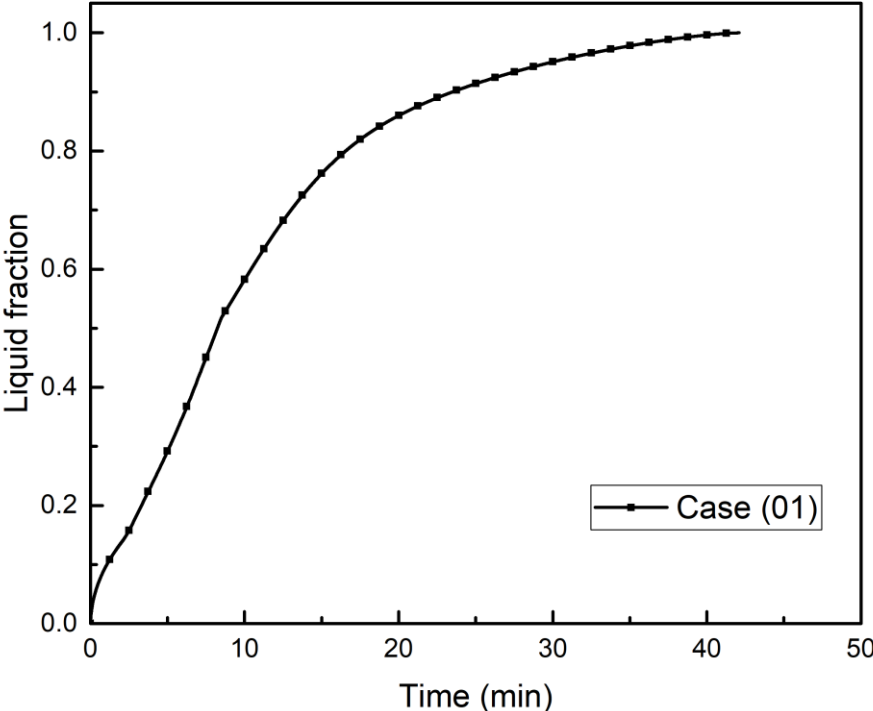


Figure IV. 2. Liquid fraction development for simulation case 01

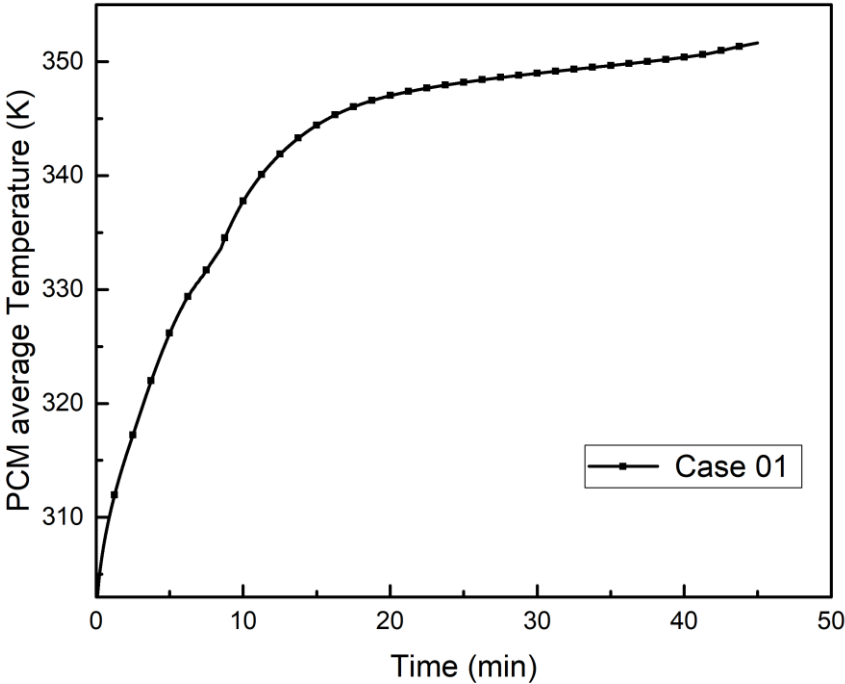


Figure IV. 3. The development of the PCM average temperature through time for simulation case 01

B. Case 02

Figure IV.4 displays the simulation results for Case 02, which involves an eccentric cylindrical heat exchanger configuration. The figure presents a sequence of cross-sectional contours illustrating the liquid fraction (a), velocity streamlines (b), and temperature distribution (c) at selected time intervals (1, 2.5, 5, 7, 11, 13, 14, and 17 minutes). The aim is to investigate how the offset position of the inner tube affects the phase change dynamics and heat transfer mechanisms. After 1 minute of heating, a thin layer of melted PCM close to the inner tube was observed, a uniform liquid fraction contour with velocity streamlines increases surrounding the inner hot cylinder. Furthermore, we've noticed that the temperature contours show a progressive decrease from the hot wall toward the outer wall, resulting the effect of heat conduction.

By 2.5 minutes, the formation of a wavy shape in the upper section of the liquid fraction contours. Although conduction still dominates, the temperature gradient is noticeably apparent near the narrow gap. Additionally, velocity streamlines start to form slight loops, signalling the start of natural convection localized around the melted zone. At 5 minutes, a distinct change is observed, convective circulation becomes clearer, especially on the upper portion, where melted PCM rises and begins to circulate. The melting front expands, and the velocity contours strengthens, with streamlines clearly indicating loops forming on the side with greater melting. By 7 minutes, this behaviour intensifies, the upper region exhibits significant liquefaction, while the lower region still shows delayed melting, a direct result of poor convective flow in the lower portion of the configuration. The temperature contours stretch more, highlighting the combined influence of conduction near the lower zones and natural convection dominating the upper region.

Between 11 and 14 minutes, natural convection is well developed, significantly accelerating the melting process. The upper half of the system is fully liquefied by minute 13. The streamlines form full convection loops, and their intensification results in better thermal performance.

By 17 minutes, most of the PCM is melted, except in lower region; the temperature gradients flatten, indicating that thermal equilibrium is nearing in large portions of the domain.

Case (02)

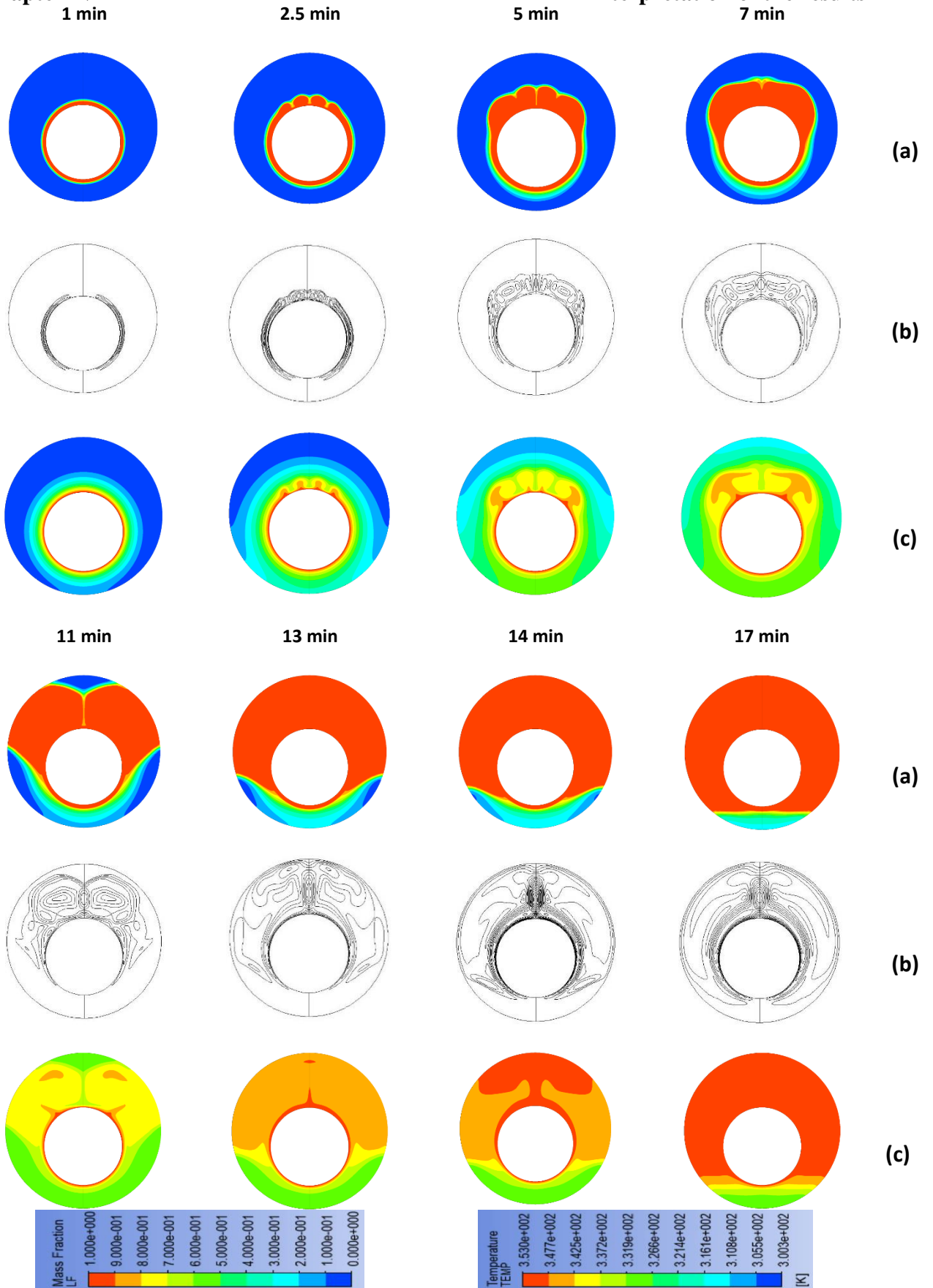


Figure IV. 4. Results of simulation Case 02 (a) liquid fraction (b) streamlines (c) temperature

Figures IV.5 and IV.6 illustrate the temporal evolution of the liquid fraction and average temperature of the PCM in the eccentric cylindrical configuration (Case 02). As we can see from the figures, The curves are divided into two parts: the first (before 13 min) are linear, showing a significant variation in both parameters as a result of heat convection, while the second (after 13 min) exhibits a decrease in variation in the latter half, as a result of thermal stratification and the return of heat conduction.

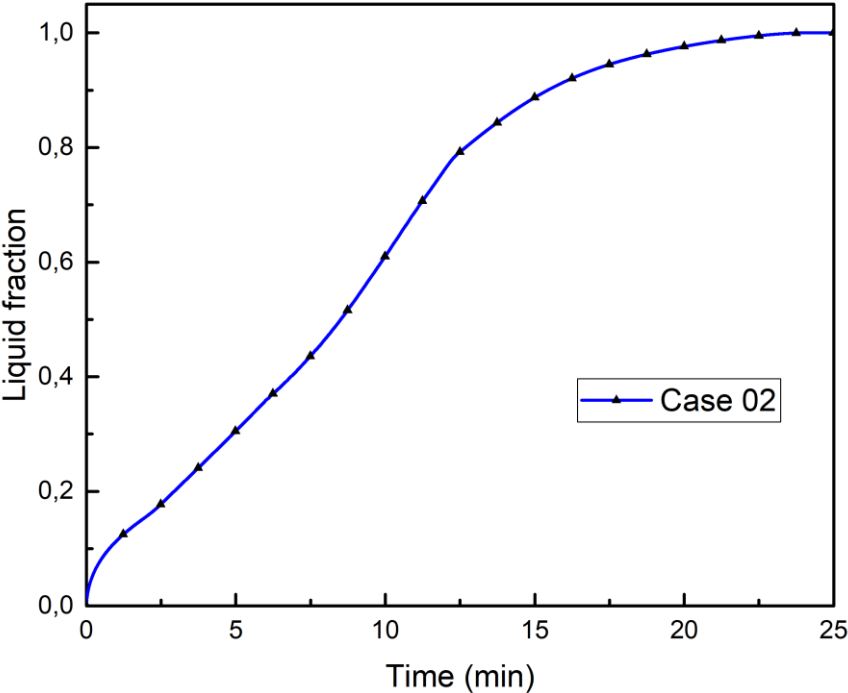


Figure IV. 5. Liquid fraction development for simulation case 02

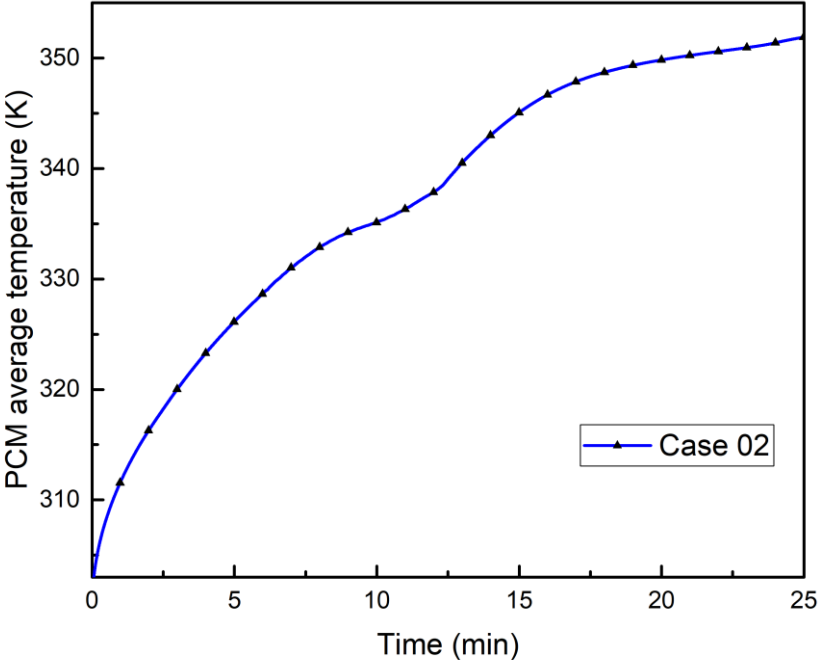


Figure IV. 6. The development of the PCM average temperature through time for simulation case 02

C. Case 03:

Figure IV.7 illustrates the simulation results for case 03, characterized by a highly eccentric cylindrical heat exchanger configuration, where the inner heated cylinder is positioned even closer to the outer wall compared to Case 02. The results are presented through a sequence of visualizations of liquid fraction (a), velocity streamlines (b), and temperature distribution (c) at selected time intervals (1, 2.5, 5, 7, 11, 13, 14, and 17 minutes).

At 1 minute, even though the PCM remains mostly solid, the melting front is notably leaning toward the narrowest region between the eccentric inner wall and the outer boundary. The liquid fraction contour shows radial expansion with higher temperature gradients in the narrow region.

By 2.5 minutes, a distinct asymmetrical melting zone between the upper and lower regions was developed. The velocity streamlines start forming, driven by localized buoyancy effects due to strong thermal gradients in the confined region; this marks a premature transition toward convection. At 5 minutes, natural convection is well-established, this circulation creates strong upward movement of the fluid and accelerates melting along the upper region, and streamlines now form full, extended loops, indicating strong convective heat transfer. The melting front spreads rapidly to adjacent regions. At 7 minutes, a large portion of the PCM has already undergone melting, particularly in the upper side of the configuration. At the lower regions, the solid PCM becomes partially melted.

As the simulation progresses to 11 and 13 minutes, the domain shows high melting completeness, especially in the upper region and near the narrow sides of the cylinder. The liquid fraction reaches advanced levels, and very few solid zones remain in the bottom part. The convection loops become stronger, reinforcing mixing in previously slower-melting regions. Temperature distributions show more uniformity at this stage. At 14 minutes, nearly 90–95% of the PCM is in a liquid state, and the system appears to be approaching thermal homogeneity.

Finally, at 17 minutes, the system is entirely liquefied. Velocity streamlines are still active, though less intense, indicating reduced thermal gradients as the system nears equilibrium. Temperature contours become smoother, suggesting efficient heat distribution throughout the domain. This increased eccentricity plays a critical role in shaping the melting behaviour of the phase change material (PCM).

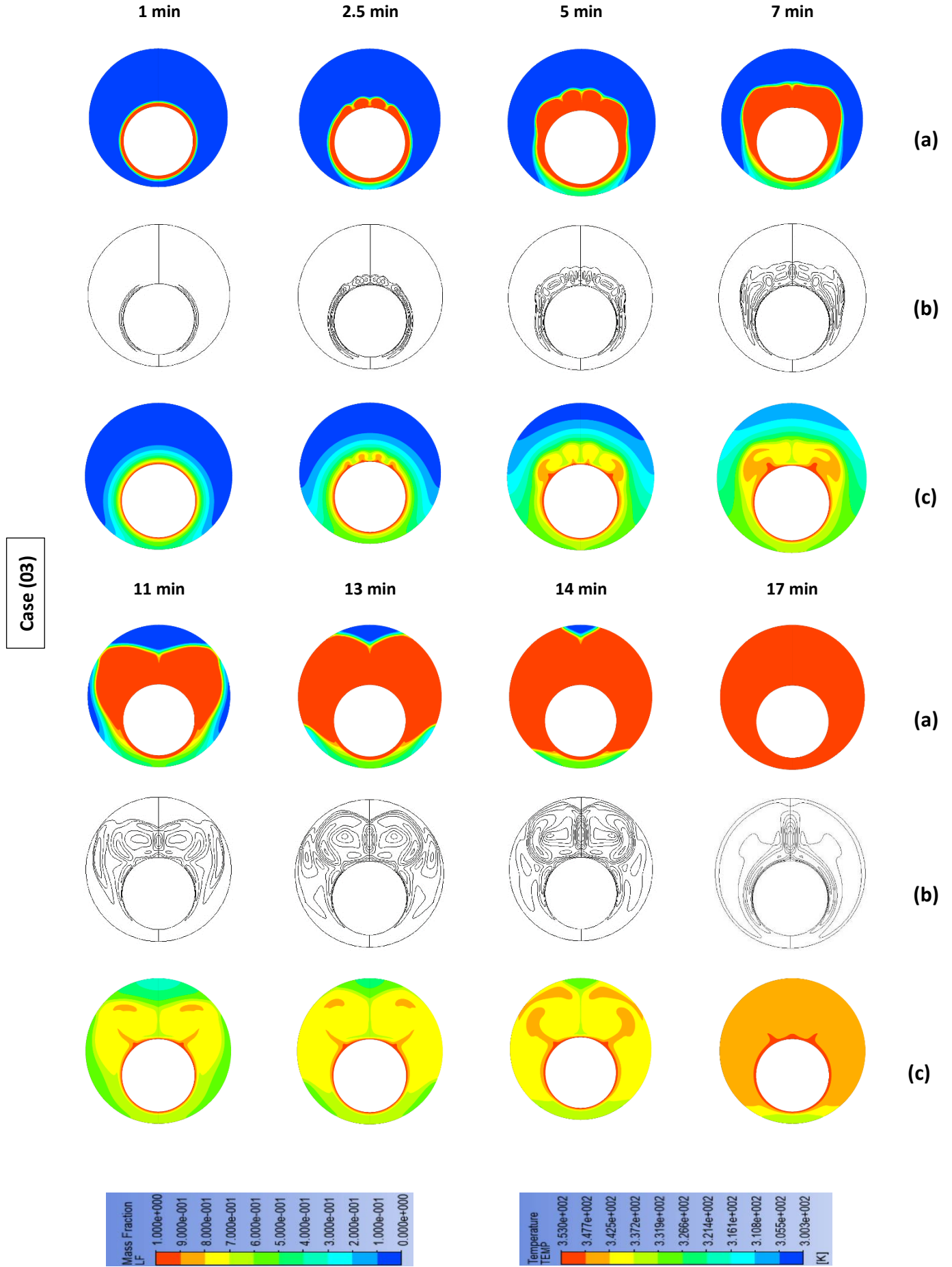


Figure IV. 7. Results of simulation Case 03 (a) liquid fraction (b) streamlines (c) temperature

Figures IV.8 and IV.9 collectively illustrate the temporal evolution of the liquid fraction and average temperature of the PCM in the eccentric cylindrical configuration (case 03). As we can see from both figures, there is a fast and steep rise in the curves, with an almost linear trend throughout the entire melting process, showing the effect of the buoyancy force in accelerating the melting process and a significant enhancement in heat transfer with minimal thermal resistance.

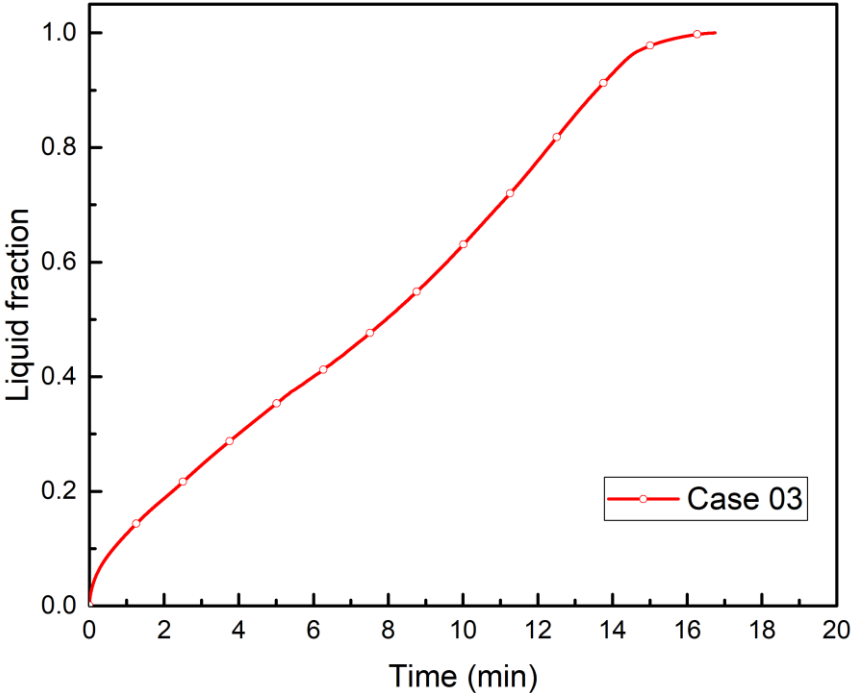


Figure IV. 8. Liquid fraction development for simulation case 03

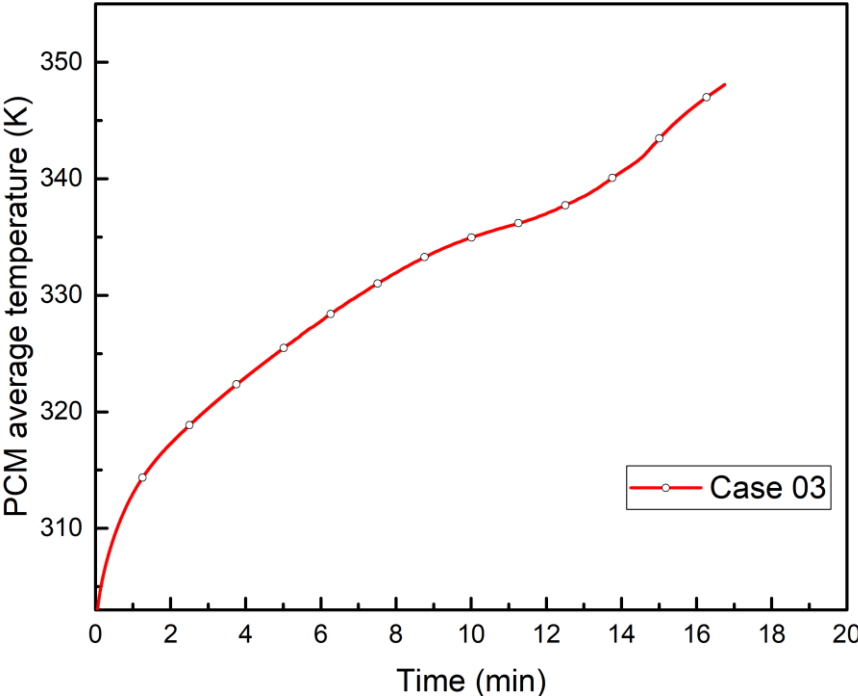


Figure IV. 9. The development of the PCM average temperature through time for simulation case 03

Comparative study:

Figure IV.10 provides a visual comparison of the melting behaviour of a phase change material (PCM) under three different geometric configurations (Cases 01, 02, and 03) over time (1, 2.5, 7, 11, and 17 minutes). These configurations, which vary in terms of the eccentric positioning of the inner cylinder, play a critical role in determining how effectively heat is transferred through the system. The evolution of the liquid fraction at the selected time intervals reveals how the interplay of geometry, conduction, convection, and thermal stratification shapes the melting process.

At 1 minute, all three cases exhibit limited melting, with the phase change largely confined to regions immediately adjacent to the heated surfaces. All three cases show a uniform radial melting pattern consistent with pure conduction.

By 2.5 minutes, we notice a slight distinction among the cases. All three cases continue to rely predominantly on conduction, with a relatively uniform progression of the melted region. The appearance of a wavy shape in the top regions signalling as early signs of natural convection beginning to emerge. The distinction In Case 03 is that the melting has slightly progressed in the narrow gap at the bottom, and the steep temperature gradient drives stronger local buoyancy forces.

At 7 minutes, convection becomes a dominant heat transfer mechanism, and its impact is evident across all cases. Case 01, while still primarily conduction dominated in the lower regions presenting the challenge of thermal stratification, it shows signs of melting acceleration in the upper central area where convective movement has finally developed. Case 02 also displays a clearer influence of convection, with expanded melt fronts both vertically and horizontally. allowing heated fluid to rise along the narrow side while cooler liquid descends, creating a more effective heat exchange loop. Case 03 shows that the melting has slightly progressed in the narrow gap at the bottom. The geometry here maximizes the thermal driving forces and convective pathways, significantly reducing the impact of thermal stratification and accelerating the melting process.

At 11 minutes, these trends intensify. Case 01 remains the slowest in terms of melting, particularly in the lower half of the domain, where conduction remains the main mechanism and thermal stratification inhibits further heat penetration. Case 02 shows more complete melting throughout the vertical extent of the domain, supported by stable and effective convective flows. Case 03, meanwhile, exhibits a near-complete melting pattern in the active

regions, with only small zones of residual solid PCM. The high eccentricity creates a narrow vertical conduit that strengthens convective currents and effectively overcomes the insulating effect of stratified layers. The combination of strong conduction in narrow regions and vigorous convection throughout the melt zone leads to superior thermal performance.

By 17 minutes, Case 03 has reached full liquefaction. Its enhanced geometry has successfully facilitated efficient melting across the entire domain by maximizing heat transfer through both conduction in the narrow gaps and convection in the wider upper zones. Case 02 also achieves significant melting, slightly trailing Case 03 but still outperforming the case 01 due to its sustained convective enhancement. Case 01, in contrast, retains a large volume of non-melted PCM, particularly near the bottom. This layout hinders the natural development of convective currents, causing heat to stagnate in the upper melted layers which is a clear appearance of thermal stratification. This creates a barrier that obstructs heat from reaching the lower solid regions, leading to an inefficient melting process even at prolonged times. The melting time for the case 01, 02 and 03 are 42, 24 and 17 minutes respectively (fig. IV. 11).

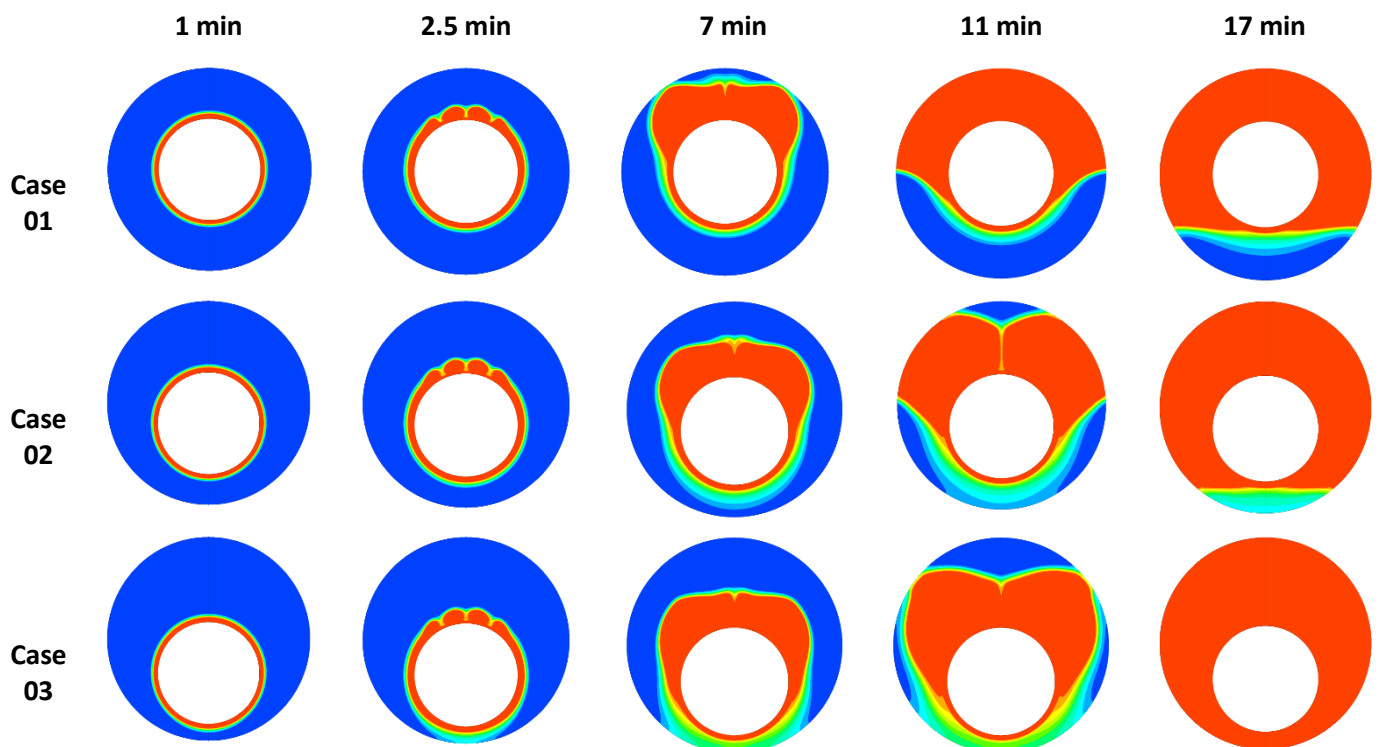


Figure IV.10. Comparison of liquid fraction at several selected times of the three simulation cases

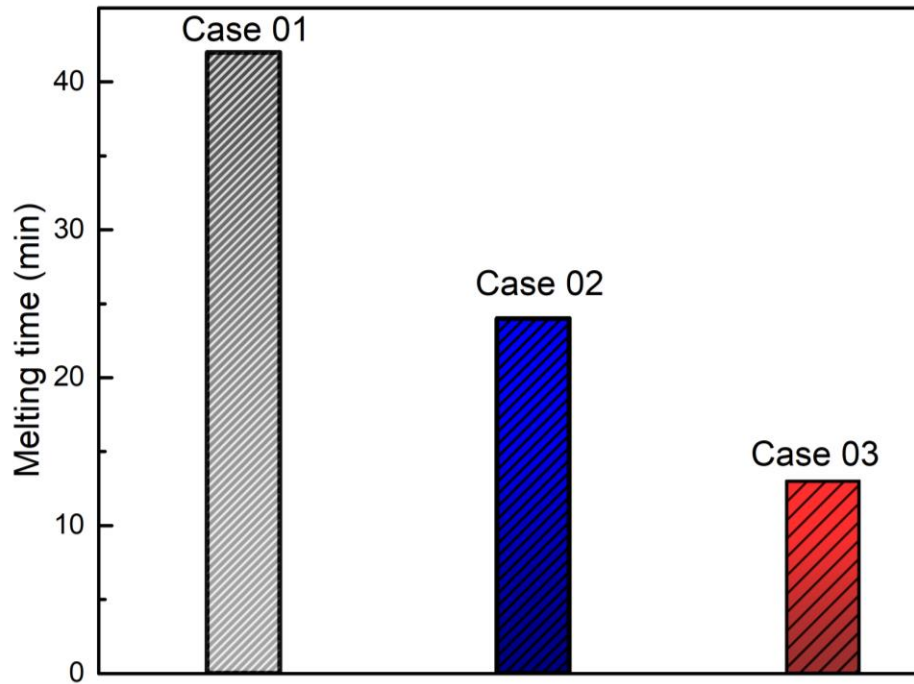


Figure IV. 11. Comparison of total melting.

IV.3 Conclusion

This chapter analysed PCM melting behaviour in three cylindrical heat exchanger configurations one concentric (Case 01) and two eccentric (Cases 02 and 03) emphasizing how geometry affects heat transfer and thermal stratification. In Case 01, the geometry led to slow, conduction-dominated melting, with weak convection and pronounced thermal stratification, especially in the lower regions, which delayed full melting. Case 02's moderate eccentricity, promoting earlier natural convection that partially tone down stratification and improved heat distribution. Case 03, with high eccentricity, showed the most efficient melting due to strong, early convection that overcame stratification entirely and promoted uniform heat transfer throughout the domain. Liquid fraction and temperature curves confirmed these trends, highlighting a faster transition from conduction to convection in eccentric cases. Overall, the study demonstrated that increasing eccentricity enhances convective flow, reduces thermal layering, and significantly improves PCM melting efficiency making it a key design strategy in thermal energy storage systems.

General

Conclusion

General conclusion

This study provides an in-depth investigation into the thermal performance of an annular heat tube exchanger system using stearic acid as a medium for thermal energy storage (TES). The study emphasizes the geometric influence of eccentricity in annular configurations on enhancing the melting process and improving heat transfer efficiency. The work simulates and compares three distinct geometric cases of concentric and eccentric cylindrical tubes: one concentric and two eccentric configurations.

The results obtained are presented as liquid fraction, average temperature, and streamlines contours, along with graphs showing the temporal evolution of the melting process and mean temperature, as well as a diagram illustrating the total melting time. The following main conclusions are drawn from the study:

- At initial time, all cases provide dominant heat conduction with circular uniform melting front near the hot inner tube.
- Buoyancy force has a significant effect in accelerating the melting process at later stages; the impact is especially notable in the upper half of the annulus for concentric case. While the eccentric systems show a greater effect by enhancing circulation and promoting the movement of the melted PCM throughout the entire system.
- Thermal stratification of the solid PCM was the big challenge in decreasing the melting rate.
- Thermal stratification decreases with increasing eccentricity. The concentric geometry takes a longer time to melt the stratified PCM, while the moderately eccentric annulus requires less time. In contrast, the highly eccentric case does not exhibit this issue.
- The highest eccentricity provides the greatest enhancement. The concentric annulus requires 42 minutes for complete melting, while the moderately eccentric case takes 24 minutes. However, Case 3, with the highest eccentricity, completes melting in just 17 minutes. This indicates that the optimal geometric configuration can enhance the melting rate by up to 40.5%.

Therefore, when integrating PCMs in TES systems, particularly for renewable energy applications, design optimization should prioritize eccentric geometries in horizontal annular systems. The findings of this research not only validate the efficacy of using organic PCMs

such as stearic acid but also provide a robust framework for future experimental validation and industrial implementation.

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