

**Democratic Republic of Algeria**  
**Ministry of**  
**Higher Education and**  
**Scientific Research**  
**Amar Telidji- Laghouat University**



**FACULTY OF TECHNOLOGY**  
**MECHANICAL ENGINEERING DEPARTMENT**  
**A dissertation submitted in partial fulfillment for the**  
**requirements of the degree of master's in mechanical engineering.**

**Presented By:**  
**RAHMOUNE AHMED**  
**KHALED ABDERAHMANE**  
**DOMAIN: SCIENCES and TECHNOLOGIES**  
**OPTION: ENERGETIC**

**Theme**

# **Study of the thermo-hydraulic behavior of an air-PCM exchanger**

**Defense jury:**  
**Member :**  
**Unknown person**  
**Mr. Unknown person**  
**Mr. BELLAHCENE Lahcene**

**Quality:**  
**President**  
**Examiner**  
**Supervisor**

**Academic Year: 2024/2025**

## ***Dedication***

*Alhamdulillah,  
All praise be to Allah who granted me the strength and patience to complete  
this work.*

*I dedicate this humble effort to the most precious people in my life: To my  
beloved father and mother, whose love, sacrifices, and prayers have been the  
light guiding my path.*

*To my dear brothers and my sister, who have supported and encouraged me  
through every step of my journey.*

*To my loyal friends, who stood by me and shared both the challenges and the  
joys along the way.*

*To all those who helped me, supported me, and believed in me during this time*

—  
*I am forever grateful.*

*And to our resilient brothers and sisters in Palestine, whose courage and  
steadfastness inspire*

*You all-are always in our hearts and prayers.*

*To all professors of the mechanical engineering department  
and especially my Supervisor **Dr. BELLAHCENE Lahcen.***

*To him who was with me by his encouragement  
and helped me to complete this work.*

***Khaled Abderahmane.***

## ***Dedication***

*In the Name of Allah, the Most Merciful, the Most Compassionate "Say, Work, for Allah will see your deeds, and so will His Messenger and the believers."*

*He is Allah — the One who makes the night beautiful through gratitude to Him, who makes the day delightful through obedience to Him, and who makes every moment precious through remembrance of Him — Glorified and Exalted is He.*

*To the one who conveyed the message and fulfilled the trust, our master Muhammad, peace and blessings be upon him — the journey has come to an end. It was neither a short journey, nor was it an easy one, nor was the dream near. Yet no matter how long the journey, it will eventually pass — with its sweetness and its hardships.*

*In this moment of great pride, I dedicate my work to the one who raised me and struggled for my sake, to the lamp that illuminated my path, and to the one whose name I carry with honor — may your life be filled with goodness, O master among men. May Allah prolong your life so that you may witness the harvest of what has been sown — my dear father.*

*To the angel in my life, the meaning of love, the comfort of my eyes, and the most precious gift I possess; To the smile of life and the secret of existence; To the one whose prayers were the key to my success and whose tenderness was the balm to my wounds — to my beloved mother, may Allah protect her. To my unshakable support who never falters; To the one whom Allah blessed me with as a refuge and a steadfast shelter; To the one who cleared the thorns of failure from my path — to my dear sister. And to my beloved brothers — my pillars and strength in life.*

***Dr. Bellahcene Lahcen.** I thank him for his time, efforts, and patience in following my progress and teaching me how to deal with research challenges with a spirit of perseverance and critical thinking. His sound advice and precise guidance motivated me toward achieving this accomplishment. All thanks, gratitude, and appreciation to him, and I ask God to bless his knowledge and work, and to guide us all to what is good and beneficial.*

***RAHMOUN AHMED.***

## **Abstract:**

This numerical investigation aims to study the storage of solar energy in horizontal heat exchanger pipe using phase change material (PCM). Focusing on its thermal performance, fluid dynamics, and energy storage efficiency. PCMs are widely used in thermal management systems due to their high energy storage density during phase transitions, making them ideal for applications such as HVAC systems, renewable energy storage, and electronic cooling. However, the interaction between air (as the heat transfer fluid) and PCM within the exchanger presents complex thermo-hydraulic challenges, including variable thermal resistance, transient heat transfer, and airflow distribution effects. The technique of heat transfer enhancement is used to understand the melting and solidification process phenomenon in a horizontal coaxial heat pipe type latent thermal energy storage (LHTES) unit. The enthalpy porosity method is used to solve the process of solidification and melting phenomenon of PCMs, using CFD code (computation fluid dynamics). The parameters studied are temperature distribution and liquid fraction to describe the charge/discharge process in the heat pipe. The computational results showed that PCM can increase the imposed temperature with  $\Delta T_{max} = 19^{\circ}C$  and  $\Delta T_{min} = 6^{\circ}C$ , and the outer air temperature fluctuated between  $38^{\circ}C - 31^{\circ}C$ .

**Key words:** Phase change materials, CFD, Numerical simulation.

## **المخلص:**

تهدف هذه الدراسة العددية إلى دراسة تخزين الطاقة الشمسية في أنبوب مبادل حراري أفقي باستخدام مادة تغير الطور (PCM)، مع التركيز على أدائه الحراري، ديناميكا المائع، وكفاءة تخزين الطاقة. تُستخدم مواد تغيير الطور على نطاق واسع في أنظمة إدارة الحرارة بفضل كثافة تخزينها العالية للطاقة أثناء عملية الانتقال الطوري، مما يجعلها مثالية لتطبيقات مثل أنظمة التدفئة والتهوية وتكييف الهواء (HVAC)، وتخزين الطاقة المتجددة، وتبريد الإلكترونيات. ومع ذلك، فإن التفاعل بين الهواء (باعتباره مائع نقل الحرارة) والـ PCM داخل المبادل الحراري يُظهر تحديات حرارية-هيدروليكية معقدة، تشمل المقاومة الحرارية المتغيرة، وانتقال الحرارة غير المستقر، وتأثيرات توزيع تدفق الهواء. تُستخدم تقنية تحسين انتقال الحرارة لفهم ظاهرة الانصهار والتجمد في وحدة تخزين طاقة حرارية كامنة (LHTES) من نوع أنبوب حراري متحد المحور أفقي.

تُستخدم طريقة الإنثالبي-المسامية لحل عملية التجمد والانصهار لمواد PCM، باستخدام كود CFD (ديناميكا الموائع الحسابية). تم دراسة معلمات مثل توزيع درجة الحرارة والجزء السائل لوصف عملية الشحن/التفريغ في الأنبوب الحراري. أظهرت النتائج الحسابية أن الـ PCM يمكن أن يرفع درجة الحرارة المفروضة بقيمة  $\Delta T_{max} = 19^{\circ}C$  و  $\Delta T_{min} = 6^{\circ}C$ ، كما تراوحت درجة حرارة الهواء الخارجي بين  $38^{\circ}C$  و  $31^{\circ}C$ .

**الكلمات المفتاحية:** المواد متغيرة الطور، ديناميكا الموائع الحاسوبية، المحاكاة العددية.

## **Résumé**

Cette étude numérique vise à analyser le stockage de l'énergie solaire dans un échangeur de chaleur horizontal utilisant un matériau à changement de phase (PCM). Elle se concentre sur la performance thermique, la dynamique des fluides et l'efficacité du stockage d'énergie. Les

PCM sont largement utilisés dans les systèmes de gestion thermique en raison de leur densité de stockage d'énergie élevée pendant les transitions de phase, ce qui les rend idéaux pour des applications telles que les systèmes CVC, le stockage d'énergie renouvelable et le refroidissement électronique.

Cependant, l'interaction entre l'air (en tant que fluide caloporteur) et le PCM dans l'échangeur présente des défis thermo-hydrauliques complexes, notamment la résistance thermique variable, le transfert de chaleur transitoire et les effets de distribution du flux d'air. La technique d'amélioration du transfert thermique est utilisée pour comprendre le phénomène de fusion et de solidification dans une unité de stockage d'énergie thermique latente (LHTES) de type tube thermique coaxial horizontal.

La méthode enthalpie-porosité est utilisée pour résoudre le processus de solidification et de fusion du PCM, à l'aide d'un code CFD (dynamique des fluides numérique). Les paramètres étudiés sont la distribution de température et la fraction liquide afin de décrire le processus de charge/décharge dans le tube thermique. Les résultats numériques ont montré que le PCM peut augmenter la température imposée avec un  $\Delta T_{\text{max}} = 19^{\circ}\text{C}$  et un  $\Delta T_{\text{min}} = 6^{\circ}\text{C}$ , tandis que la température de l'air extérieur variait entre  $38^{\circ}\text{C}$  et  $31^{\circ}\text{C}$ .

**Mots-clés :** Matériaux à changement de phase, CFD, Simulation numérique.

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### NOMENCLATUR

<b>SYMBOLES</b>	<b>PARAMETER</b>	<b>UNITE</b>
$T$	temperature	(°C, °K)
$T_p$	the wall temperature	(°C, °K)
$T_m$	melting temperature	(°C, °K)
$T_\infty$	the temperature away from the wall.	(°C, °K)
$\Delta T$	temperature difference characteristic of the system studied	(°C, °K)
$T_l$	Refers to the temperature of the metal in the liquid state	(°C, °K)
$T_s$	Refers to the temperature of the metal in the solid state	(°C, °K)
$T_f$	Désigne la température de solidification (fusion)	(°C, °K)
$t$	Time	(s)
$m$	mass of the storage martial	(Kg)
$C_p$	specific heat capacity	(j/kg.k)
$Q_{in}$	heat inpute rate	(w)

$Q_{out}$	heat loss rate	(w)
$\dot{Q}_{loss}$	Heat loss	(w)
$h$	Convection Heat transfer coefficient	(W/m <sup>2</sup> .K)
$A$	Surface area	(m <sup>2</sup> )
$k$	Thermal conductivity	(W/m.K)
$L$	Insulation thickness	(m)
$\Delta h_{fus}$	Latent Heat of fusion	(J/kg).
$\dot{m}$	Rate of phase change.	(kg/s)
$\rho$	Density of the material	(kg/m <sup>3</sup> )
$\nabla \cdot (k\nabla T)$	heat conduction term (Fourier's Law).	(W/m <sup>3</sup> )
$\rho\Delta h_{fus} \frac{\partial f}{\partial t}$	heat source /sink due to phase change.	(W/m <sup>3</sup> )
$X$	extent of reaction	(mol)
$\frac{dX}{dt}$	reaction rate.	(mol/s)
$\frac{dE_{stored}}{dt}$	rate of change of stored energy.	(W)
$\eta$	The thermal efficiency	(%)
$h$	is a positive quantity called the convective exchange coefficient	(m <sup>-2</sup> k <sup>-1</sup> w.)
$S$	is the heat exchange surface.	(m <sup>2</sup> )
$L_C$	is a characteristic length of the system studied	(m).
$\nu$	is the kinematic viscosity of the fluid	(m <sup>2</sup> /s)
$\mu$	is the dynamic viscosity of the fluid	(Pa·s)
$\beta$	is the coefficient of thermal expansion	(K <sup>-1</sup> )
$L_c$	is a characteristic length of the system studied	(m)
$\alpha$	is the thermal diffusivity of the fluid	(m <sup>2</sup> )
$\lambda$	the thermal conductivity of the fluid	(W.m <sup>-1</sup> .k <sup>-1</sup> )
$N$	specific heat of the fluid	(J/kg·K)
$\emptyset$	Quantity of heat exchanged	(W·s)
$\sigma$	Constant of STEFAN BOLTZMANN	(5.67×10 <sup>-8</sup> W/m <sup>2</sup> ·K <sup>4</sup> )
$S$	Exchange surface	(m <sup>2</sup> )
$h_{ref}$	the enthalpy at the reference temperature	(J/kg)
$f$	Liquide fraction	
$Re$	Reynolds number	
$Gr$	Grashof Number	
$\epsilon$	Thermal emissivity of the material	

# **General Introduction**

# General Introduction

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A Phase Change Material is a substance that stores and releases large amounts of thermal energy during the process of melting or solidifying. During the phase transition, the material absorbs or releases latent heat at a nearly constant temperature.

This numerical investigation aims to study the storage of solar energy in horizontal heat exchanger pipes using phase change material (PCM). The technique of heat transfer enhancement is used to understand the melting and solidification process phenomenon in a horizontal coaxial heat pipe type latent thermal energy storage (LHTES) unit. The enthalpy porosity method is used to solve the process of solidification and melting phenomenon of PCMs, using CFD code (computation fluid dynamics). The parameters studied are temperature distribution and liquid fraction to describe the charge/discharge process in the heat pipe.

This dissertation is composed of four chapters; the first chapter is General Introduction to Phase Change Materials including the types of PCMs and the selection criteria for a PCM also the thermal energy storage the definition and the types each of them, Additionally the application for PCM, this chapter introduces the measurement of thermal properties of PCM and the advantages and disadvantages of PCM.

The second chapter Generality regarding Heat, Transfer the concept of heat and the heat transfer mechanisms the definition and the application.

The third chapter will be focused on the most important Numerical methods for solid-liquid phase-change problems, the different functions used for each method which is Solidification theory and the Numerical Methods.

The fourth chapter focuses on the discussion and the results analysis of numerical results, We have similar contents to the PCM with The Ansys Fluent program. As we see in the steps and the final Consequence.

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# **Chapter I**

## **General Introduction to Phase Change Materials**

## I.1-Introduction

In many countries, buildings consume approximately 40% of the global energy demand, with around 60% of this energy used for heating and cooling, making them among the largest energy consumers. This excessive energy consumption contributes significantly to environmental challenges such as climate change and ozone layer depletion. Algeria faces similar environmental concerns, exacerbated by the need to preserve its fossil fuel resources, which constitute a major part of its energy supply and exports. [1]

To mitigate these issues, improving building envelope designs and carefully selecting construction materials can significantly reduce energy demand. One of the most promising solutions in this field is the use of Phase Change Materials (PCMs), which provide efficient thermal energy storage by utilizing latent heat during phase transitions. Unlike conventional materials that store heat through sensible heat processes, PCMs have the advantage of high energy storage density, allowing for better thermal regulation in a confined space. [2]

## I.2-Fundamentals of Phase Change Materials (PCMs)Based on their physical state, PCMs are categorized into:

### I.2.1 Working Principle of PCMs:

PCMs absorb or release large amounts of latent heat during phase transitions (solid↔liquid, liquid↔gas). Unlike sensible heat storage, where temperature changes with energy input, PCMs store energy at a nearly constant temperature.

**Example:** Ice (at 0°C) absorbs 334 kJ/kg when melting, much more than water heating sensibly (4.18 kJ/kg·K).

### I.2.2 Key Thermophysical Properties of PCMs

Property	Importance	Ideal Value
Latent Heat ( $\Delta H$ )	Energy storage capacity.	>150 kJ/kg
Melting Temperature ( $T_m$ )	Must match application.	Depends on use case
Thermal Conductivity ( $k$ )	Heat transfer efficiency.	>0.5 W/m·K
Density ( $\rho$ )	Volumetric storage capacity.	High
Supercooling Degree	It should be minimal.	<5°C
Cycling Stability	Long-term reliability.	>10,000 cycles
Cost & Toxicity	Economic & environmental impact.	Low

Table I.1: Key Thermophysical Properties of PCMs.

### I.2.3 Types of Phase Transitions in PCMs

- **I.2.3.1 Solid-Solid PCMs:** Change crystalline structure without melting (e.g., layered perovskites).
- **I.2.3.2 Solid-Liquid PCMs:** Most common (e.g., paraffins, salt hydrates).
- **I.2.3.3 Liquid-Gas PCMs:** Rarely used due to large volume changes. PCMs are further classified into.

### I.2.4 Classification and Examples of PCMs:

- **I.2.4.1 Organic PCMs:** Including paraffins and fatty acids, these materials exhibit good thermal stability and non-corrosiveness.

#### Paraffins ( $C_nH_{2n+2}$ )

- **Advantages:** High latent heat, chemically stable, non-corrosive.
- **Disadvantages:** Low thermal conductivity ( $\sim 0.2 \text{ W/m}\cdot\text{K}$ ), flammable.
- **Examples:**
  - Octadecane ( $C_{18}H_{38}$ ,  $T_m \approx 28^\circ\text{C}$ ) – Building applications.
  - Eicosane ( $C_{20}H_{42}$ ,  $T_m \approx 37^\circ\text{C}$ ) – Solar water heating.

#### Non-Paraffins (Fatty Acids, Esters, Alcohols)

- **Advantages:** Better thermal stability, lower supercooling.
- **Disadvantages:** Higher cost.
- **Examples:**
  - Capric acid ( $T_m \approx 32^\circ\text{C}$ ) – Textile thermal regulation.
    - Erythritol ( $T_m \approx 118^\circ\text{C}$ ) – Industrial waste heat recovery.
- **I.2.4.2 Inorganic PCMs:** Such as salt hydrates and metallic compounds, they offer high thermal conductivity but may suffer from supercooling and phase segregation.

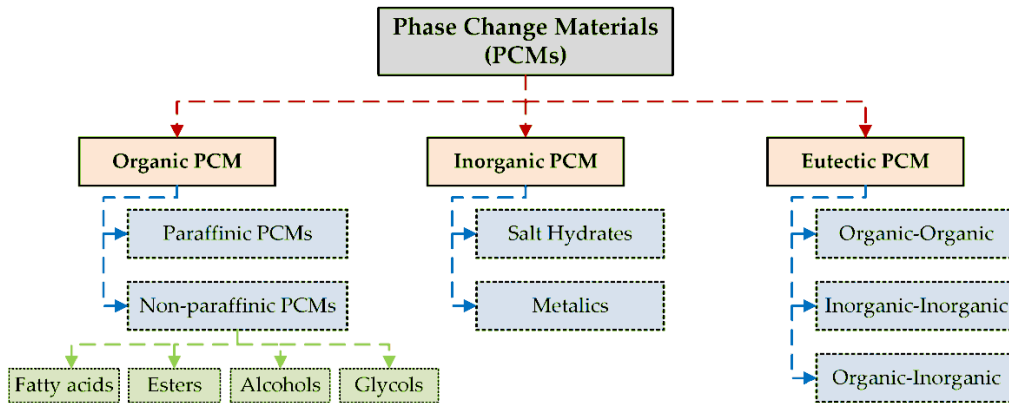
#### Salt Hydrates ( $M_nH_2O$ )

- **Advantages:** High latent heat, high thermal conductivity ( $\sim 0.5 \text{ W/m}\cdot\text{K}$ ).
- **Disadvantages:** Phase segregation, supercooling.
- **Examples:**
  - Sodium sulfate decahydrate (Glauber's salt,  $T_m \approx 32^\circ\text{C}$ ).
  - Calcium chloride hexahydrate ( $T_m \approx 29^\circ\text{C}$ ).

#### Metallic PCMs (Low-Melting Alloys)

- **Advantages:** Extremely high conductivity ( $\sim 10\text{--}50 \text{ W/m}\cdot\text{K}$ ).
- **Disadvantages:** Heavy, expensive.
- **Examples:**
  - Gallium ( $T_m \approx 30^\circ\text{C}$ ) – Electronics cooling.
  - Field's metal ( $T_m \approx 62^\circ\text{C}$ ) – High-temperature storage.

- **I.2.4.3 Eutectic PCMs:** A combination of organic and inorganic materials, these PCMs provide tailored thermal properties with reduced phase separation issues [4].
- **Advantages:** Tailored melting points, reduced supercooling.
- **Examples:**
  - Lauric acid + stearic acid ( $T_m \approx 35^\circ\text{C}$ ).
  - $\text{LiNO}_3 + \text{KCl}$  ( $T_m \approx 130^\circ\text{C}$ ) – Concentrated solar power (CSP).



**Figure I.1:** Phase change materials (PCMs) categories.

## I.3-Selection Criteria for Phase Change Materials

Choosing an appropriate PCM for thermal energy storage depends on several factors:

### I.3.1 Thermal Properties:

- **Phase Transition Temperature:** The PCM should operate within the desired temperature range.
- **High Latent Heat Capacity:** More energy can be stored per unit mass.
- **Thermal Conductivity:** Higher conductivity improves heat transfer rates.

### I.3.2 Physical Properties:

- **Density:** A higher density enables compact storage.
- **Volume Expansion:** Minimal expansion reduces structural stress.
- **Phase Stability:** Ensures long-term performance and efficiency.

### I.3.3 Chemical Properties:

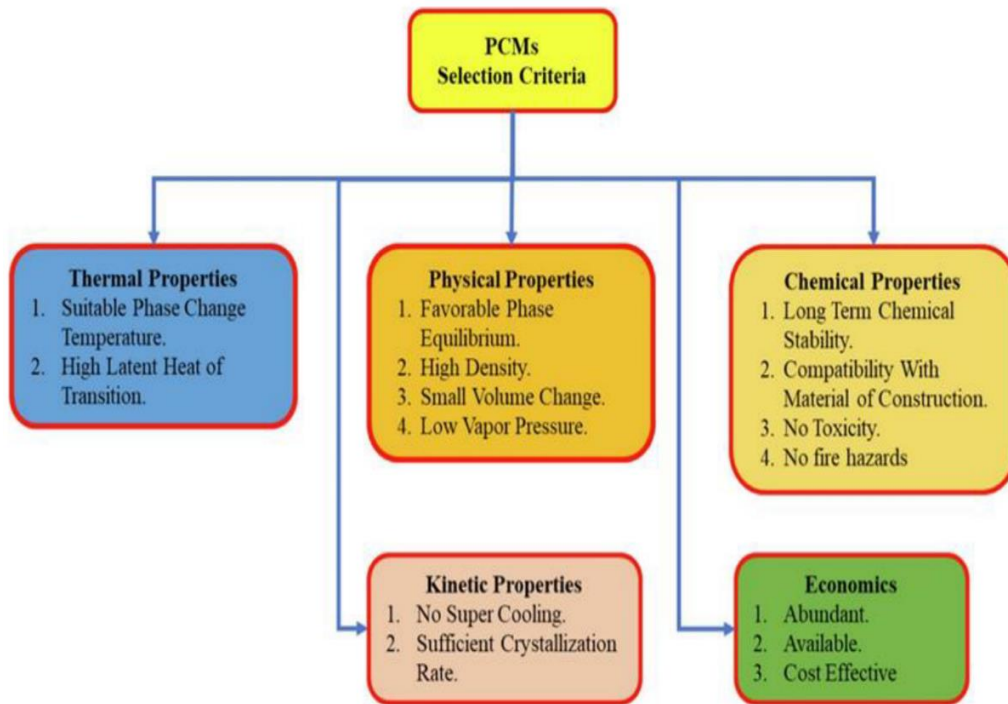
- **Stability Over Time:** Prevents degradation through repeated melting/solidification cycles.
- **Compatibility with Storage Materials:** Avoids corrosion or unwanted chemical reactions.
- **Non-Toxicity and Safety:** Ensures environmental and user safety.

**I.3.4 Economic Aspects:**

- **Cost:** The material should be cost-effective for large-scale applications.
- **Availability:** Widespread availability ensures feasibility.
- **Sustainability:** Recyclability and environmental impact should be considered.

**I.3.5 Kinetic Properties**

- Supercooling must be reduced.
- A high crystallization rate.[5]



**Figure I.2:** Various criteria for the selection of PCM.

**I.4-Thermal Energy Storage**

**I.4.1-Definition**

Thermal energy storage (TES) is a crucial aspect of energy management and plays a fundamental role in the integration of renewable energy systems. TES enables excess thermal energy to be stored and used later, enhancing energy efficiency and sustainability. The main classifications of TES systems are:

**I.4.1.1 Sensible Heat Storage (SHS):**

Sensible heat storage relies on the heat capacity of a material and its temperature change.

**Energy stored in SHS**

The stored thermal energy ( $Q_{stored}$ ) is given by:

$$Q_{stored} = m \cdot c_p \cdot \Delta T \quad (I. 1)$$

Where:

- ❖  $m$ =mass of the storage material(kg).
- ❖  $C_p$ =specific heat capacity(j/kg.k).
- ❖  $\Delta T=T_{final} - T_{initial} = \text{temperature change}(k)$ .

## Thermal Balance for SHS

For a well-insulated storage system, the energy balance is:

$$Q_{in} - Q_{out} = m \cdot C_p \frac{dT}{dt} \quad (\text{I. 2})$$

Where:

- ❖  $Q_{in}$ =heat input rate(w).
- ❖  $Q_{out}$ =heat loss rate (w).
- ❖  $\frac{dT}{dt}$ =rate of temperature change.

If heat loss is considered (e.g., through convection and conduction):

$$Q_{loss} = h \cdot A \cdot (T_{storage} - T_{ambient}) + \frac{k \cdot A}{L} \cdot (T_{storage} - T_{ambient}) \quad (\text{I. 3})$$

Where:

- ❖  $h$ =convection heat transfer coefficient ( $W/m^2 \cdot K$ ).
- ❖  $A$ =surface area ( $m^2$ ).
- ❖  $k$ =thermal conductivity ( $W/m \cdot K$ ).
- ❖  $L$ =insulation thickness(m).

### I.4.1.2 Latent Heat Storage (LHS):

LHS uses phase change materials (PCMs) to store energy as latent heat during melting/solidification.

## Energy stored in LHS

The total energy stored includes sensible and latent heat:

$$Q_{total} = m \left[ \int_{T_{initial}}^{T_m} C_{p,solide} dT + \Delta h_{fus} + \int_{T_m}^{T_{final}} C_{p,liquid} dT \right] \quad (\text{I. 4})$$

Where:

- ❖  $\Delta h_{fus}$ : latent heat of fusion (J/kg).
- ❖  $T_m$ =melting temperature (k).

For isothermal phase change (constant  $T_m$ ):

$$Q_{latent} = m \cdot \Delta h_{fus} \quad (\text{I. 5})$$

## Thermal Balance for LHS

The energy balance during melting/freezing is:

$$Q_{in} - Q_{out} = m \left( c_p \frac{dT}{dt} + \Delta h_{fus} \frac{df}{dt} \right) \quad (I. 5)$$

Where:

- ❖  $f$ =liquid fraction ( $0 \leq f \leq 1$ ).
- ❖  $\frac{df}{dt}$ = rate of phase change.
- ❖ The heat transfer in PCMs is governed by:

$$\rho c_p \frac{\partial T}{\partial t} = \nabla \cdot (k \nabla T) + \rho \Delta h_{fus} \frac{\partial f}{\partial t} \quad (I. 6)$$

Where:

- ❖  $\rho$ =Density of the material ( $\text{kg/m}^3$ ).
- ❖  $T$ = Time (s).
- ❖  $\nabla \cdot (k \nabla T)$ =heat conduction term (Fourier s Law).
- ❖  $\rho \Delta h_{fus} \frac{\partial f}{\partial t}$ =heat source /sink due to phase change.

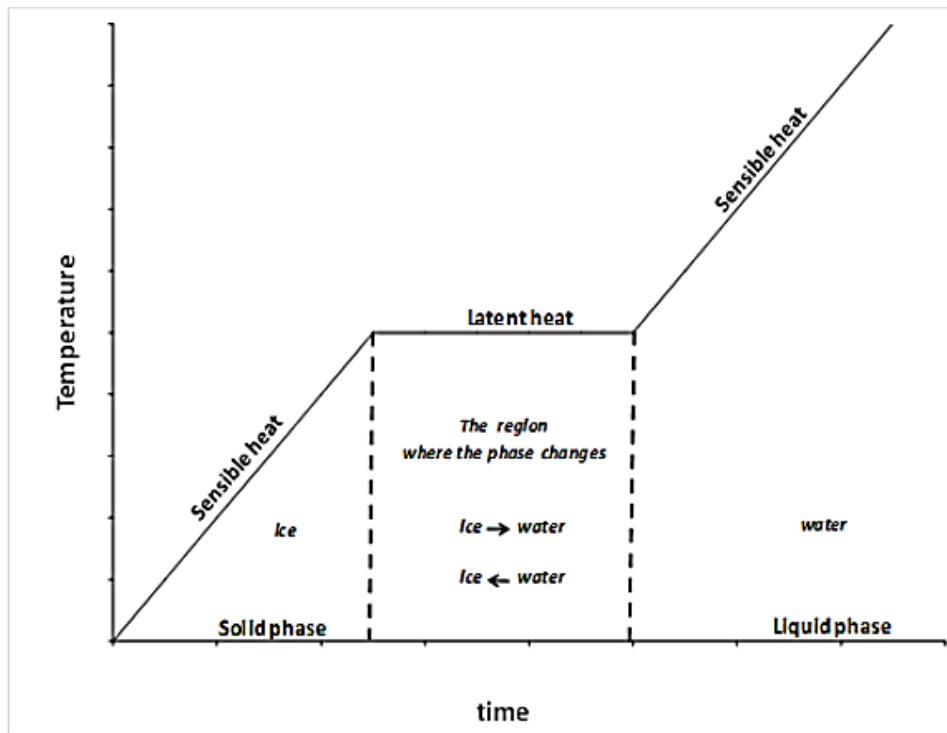


Figure I.3: Phase change profile for latent heat storage.

### I.4.1.3 Thermochemical Energy Storage (TCS):

TCS stores energy via reversible chemical reactions (e.g., adsorption, chemical reactions).

Energy stored in TCS

## Chapter I: General Introduction to Phase Change Materials

The energy stored depends on the reaction enthalpy:

$$Q_{stored} = m \cdot \Delta h_{rxn} \quad (\text{I. 7})$$

Where  $m \cdot \Delta h_{rxn}$  =reaction enthalpy (J/kg).

Thermal Balance for TCS

The energy balance includes heat of reaction and heat losses:

$$Q_{in} - Q_{out} = m \left( C_p \frac{dT}{dt} + \Delta h_{rxn} \frac{dX}{dt} \right) \quad (\text{I. 8})$$

Where:

- ❖  $X$ =extent of reaction( $0 \leq X \leq 1$ ).
- ❖  $\frac{dX}{dt}$ =reaction rate.

### I.4.1.4 Overall thermal Balance in TES systems

For any TES system, the general energy balance is:

$$\dot{Q}_{in} - \dot{Q}_{out} - \dot{Q}_{loss} = \frac{dE_{stored}}{dt} \quad (\text{I. 9})$$

Where:

- $\dot{Q}_{in}$ =input power(W).
- $\dot{Q}_{out}$ =extracted power(W).
- $\dot{Q}_{loss}$ =heat loss(W).
- $\frac{dE_{stored}}{dt}$ =rate of change pf stored energy.

### Efficiency of TES

The thermal efficiency( $\eta$ )is:

$$\eta = \frac{Q_{extracted}}{Q_{stored}} = 1 - \frac{Q_{loss}}{Q_{stored}} \quad (\text{I. 10})$$

**Table I.2:** the different parameters of each equation.

parameter	Equation
Sensible heat storage	$Q = m \cdot c_p \cdot \Delta T$
Latent heat storage	$Q = m \cdot \Delta h_{fus}$
Thermochemical storage	$Q = m \cdot \Delta h_{rxn}$
Heat lose(convection)	$Q_{loss} = hA(T_s - T_\infty)$
Heat loss (conduction)	$Q_{loss} = \frac{kA}{L} (T_s - T_\infty)$

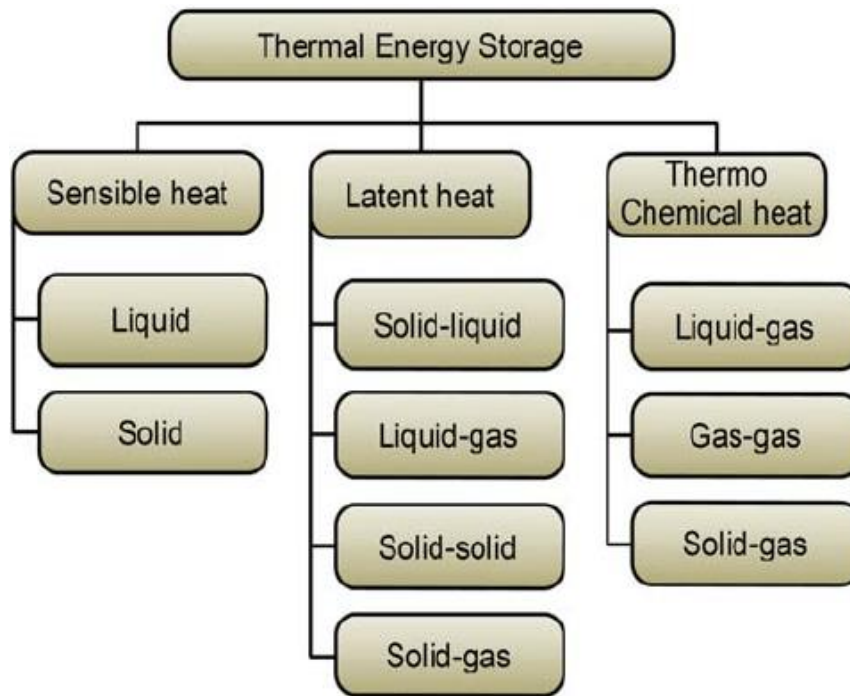
Thermal Efficiency	$\eta = \frac{Q_{out}}{Q_{in}}$
--------------------	---------------------------------

**I.4.2 Advantages of Thermal Energy Storage**

**I.4.2.1 Energy Savings:** TES reduces the demand for heating and cooling energy, leading to lower energy bills.

**I.4.2.2 Load Shifting:** TES can help balance energy supply and demand by storing excess energy during off-peak hours and releasing it during peak periods.

**I.4.2.3 Environmental Benefits:** By integrating TES with renewable energy sources, carbon emissions and reliance on fossil fuels can be significantly reduced. [3]



**Figure I.4:** Different possible methods of thermal energy storage

**I.5-Applications for Phase Change Materials**

Phase change materials (PCMs) are extensively used now a days in energy storage devices and applications worldwide. PCMs play a substantial role in energy storage for solar thermal applications and renewable energy sources integration. High thermal storage density with a moderate temperature variation can be attained by phase change materials (PCMs). Considerable research has been carried out into energy storage to achieve better efficiency and performance. Phase change Materials (PCMs) available in various temperature ranges have proved efficient in solar thermal energy storage situations. Incorporating PCMs in solar applications resulted in enhancement in the order of 12 to 87% in thermal efficiencies of the systems. Thermo-physical Properties are the basis of selecting the type of PCM for specific solar applications. PCMs like  $MgCl_2 \cdot 6H_2O$ , Mg

$(\text{NO}_3)_2 \cdot 6\text{H}_2\text{O}$ ,  $\text{CaCl}_2 \cdot 6\text{H}_2\text{O}$ , Paraffin wax,  $\text{CH}_3(\text{CH}_2)_{16}\text{CH}_3$ ,  $\text{CH}_3(\text{CH}_2)_{11}\text{OH}$  have proved successfully in solar thermal and thermo-electrical applications. [6].

### Electronics & Battery Cooling:

Thermal management within the overall design of electronic products is increasingly important since each new generation of electronic devices squeezes more power and performance into ever-smaller packages. In recent years, phase change materials (PCMs) have been widely examined as alternative cooling methods for such transient electronic cooling applications as personal computing, wearable computers, mobile phones, digital video cameras, etc. Passive thermal management using PCMs is suitable for applications where heat dissipation is intermittent or transient. Among the advantages of PCM are high latent heat of fusion giving high energy density, high specific heat, controllable temperature stability, and small volume change on phase change. Heat is stored (withdrawn from the hot component) during melting and is released to the ambient during the freezing period. Used in thermal management of batteries, processors, and LEDs to prevent overheating.

Smartphones/Laptops: Prevent overheating.

Electric Vehicle Batteries: Maintain optimal temperature.

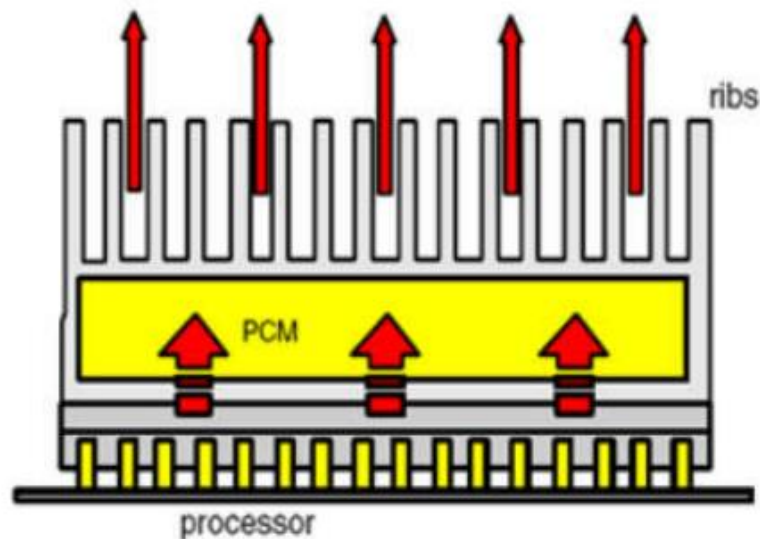


Figure I.5: MCP in cooling electronic components.

### Mechanical Engineering:

Phase Change Materials (PCMs) are increasingly applied in mechanical engineering to enhance thermal management systems, particularly in vehicle engine preheating. By storing thermal energy during engine operation and releasing it during cold starts, PCMs

## Chapter I: General Introduction to Phase Change Materials

reduce the need for prolonged idling, improving fuel efficiency and lowering emissions. These materials absorb and release heat at specific phase transition temperatures, ensuring optimal engine performance in low-temperature conditions. Additionally, PCMs are used in battery thermal management, HVAC systems, and waste heat recovery, making them a sustainable solution for energy conservation in automotive and industrial applications.

### Medical Field:

PCMs play a crucial role in the medical field by providing precise temperature control for sensitive applications. They are widely used in cold storage for vaccines, maintaining stable temperatures during transport and storage to ensure efficacy. In organ transplantation, PCM-based containers keep organs at optimal temperatures, extending preservation times. Additionally, PCMs are incorporated into therapeutic heating pads and cooling garments, offering controlled thermal therapy for pain relief, injury recovery, and fever management. Their ability to absorb, store, and release heat at specific temperatures makes them invaluable for enhancing reliability and safety in medical temperature-sensitive processes.

Vaccine Transport: Maintain stable 2–8°C range.



**Figure I.6:** Containers containing blood and organs that contain PCMs.

- **Roads and Infrastructure:**

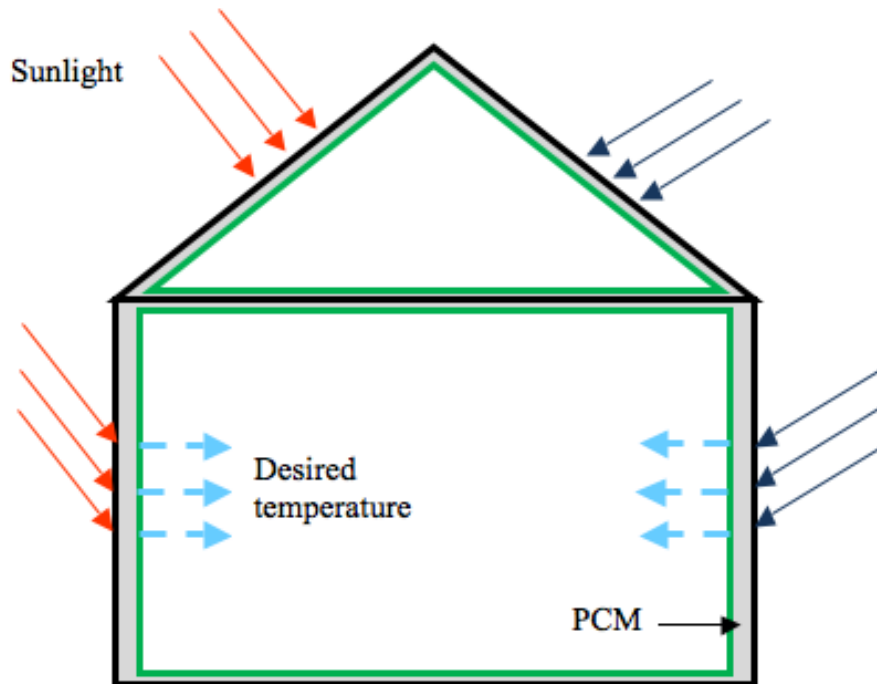
PCMs are being innovatively integrated into roads and infrastructure to enhance durability and reduce winter maintenance costs. By embedding PCMs within pavement systems, they absorb excess heat during warmer periods and release it during freezing conditions, preventing ice formation and minimizing the need for chemical deicers or salt. This not only improves road safety but also extends pavement lifespan by reducing thermal cracking and freeze-thaw damage. Additionally, PCM-enhanced infrastructure can help mitigate urban heat island effects in cities. These sustainable thermal-regulating solutions demonstrate the potential of PCMs to revolutionize smart, climate-resilient infrastructure.

- **Buildings & Construction**

PCMs are transforming building energy efficiency by being incorporated into walls, roofs, and windows to passively regulate indoor temperatures. These materials absorb excess heat during peak daytime temperatures and release it at night, smoothing out temperature fluctuations and reducing reliance on HVAC systems. When integrated into gypsum boards, insulation, or glazing systems, PCMs help maintain thermal comfort while cutting heating and cooling energy consumption by up to 30%. This technology is particularly valuable in achieving net-zero energy buildings and meeting sustainable construction standards, offering an eco-friendly solution to reduce both energy costs and carbon footprints in residential and commercial structures.

PCM-Enhanced Walls: Reduce HVAC load by 20–30%.

Thermal Energy Storage Tanks: Store solar heat for nighttime use.



**Figure I.7:** Typical Application of PCM in Buildings.

- **Solar Thermal & CSP Systems**

Parabolic Troughs: Store heat at 200–400°C using molten salts.

### I.6-Measurement of Thermal Properties of PCMs

To ensure the performance and reliability of PCMs, various testing techniques are used:

- **Differential Scanning Calorimetry (DSC):**

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is a thermal analysis technique that measures the heat flow associated with phase transitions in a material as a function of temperature or time. By comparing the sample to a reference under controlled heating or cooling, DSC detects transitions such as melting, crystallization, glass transitions, and chemical reactions. The technique provides quantitative data on transition temperatures and latent heat capacity, making it valuable for characterizing polymers, pharmaceuticals, metals, and other materials. DSC is widely used in research and industry to study thermal stability, purity, and material compatibility.



**Figure I.8:** Differential Scanning Calorimeter.

- **Thermogravimetric Analysis (TGA):**

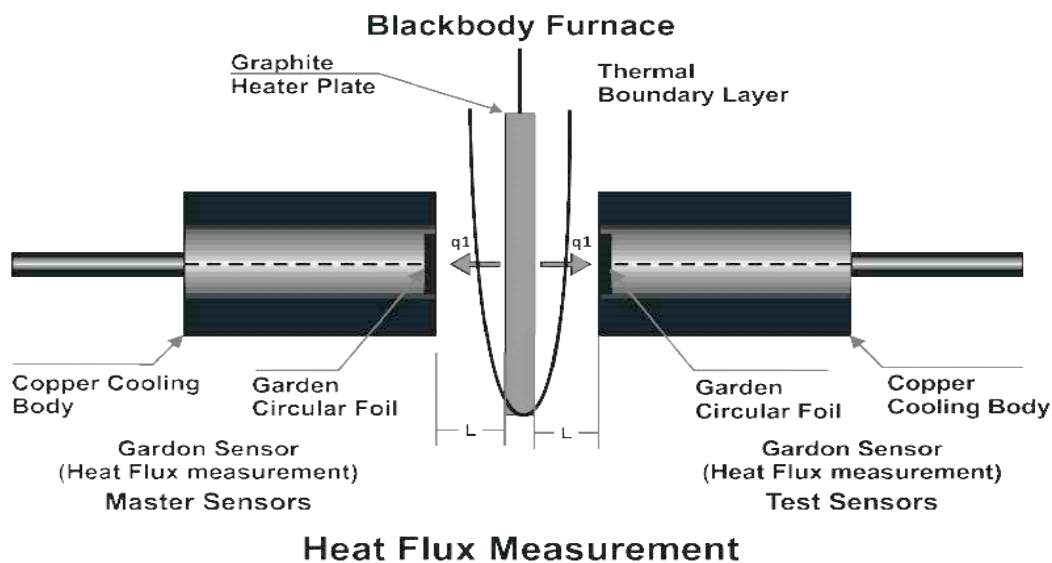
is a thermal analysis technique that measures the change in a material's mass as it is heated or cooled under a controlled atmosphere. By monitoring weight loss or gain overtime or temperature, TGA assesses thermal stability, decomposition, oxidation, and moisture content.



**Figure I.9:** Thermogravimetric Analyzer.

This method is particularly useful for studying polymer degradation, inorganic material decomposition, and filler content in composites. TGA provides critical data on decomposition temperatures, residue formation, and reaction kinetics, making it essential in materials science, pharmaceuticals, and quality control applications.

- **Heat Flux Sensors:** Evaluate thermal conductivity and heat absorption rates.
- are devices that measure the rate of heat transfer (thermal flux) through a material or across a surface. By quantifying heat flow in watts per square meter ( $\text{W}/\text{m}^2$ ), these sensors evaluate thermal conductivity, insulation efficiency, and heat absorption rates. They are widely used in building energy audits, industrial process monitoring, and aerospace applications to assess thermal performance. Common types include thermopile-based and gradient-based sensors, which provide real-time data for optimizing heating/cooling systems, improving material design, and ensuring safety in high-temperature environments. Their accuracy and reliability make them essential tools in thermal management research and engineering.



1. **Figure I.10:** Heat Flux Measurement System.

### I.7-Advantages and Disadvantages of PCMs

#### Advantages:

- **Efficient Thermal Storage:** PCMs provide higher energy density than sensible heat storage materials.
- **Enhanced Energy Efficiency:** Reduces energy consumption in heating and cooling applications.

- **Comfort Improvement:** Helps maintain consistent indoor temperatures, improving user comfort.
- **Renewable Energy Integration:** Facilitates energy storage in solar and wind-powered systems.
- **Long Lifespan:** PCMs can undergo many phase change cycles without significant degradation.

### Disadvantages:

- **High Initial Cost:** Advanced PCMs and their containment systems can be expensive.
- **Limited Temperature Range:** Each PCM is effective only within a specific temperature window.
- **Supercooling Issues:** Some inorganic PCMs may not solidify at their expected freezing points.
- **Phase Separation:** Repeated melting and solidification may cause material degradation.
- **Low Thermal Conductivity:** Many PCMs require enhancement techniques (e.g., finned structures, graphite additives) to improve heat transfer [7].

## I.8-Conclusion

Phase Change Materials (PCMs) represent a promising solution for efficient thermal energy storage and management. Their ability to absorb and release significant amounts of heat through phase.

Transitions make them ideal for applications in buildings, electronics, healthcare, and renewable energy systems. Despite existing challenges such as cost and phase separation, ongoing research and technological advancements are continuously improving their performance and feasibility. With further developments, PCMs can play a crucial role in enhancing energy efficiency and promoting sustainability in various industries.

*Chapter II*  
*Generality regarding*  
*Heat Transfer*

## II.1 Introduction:

Heat transfer is a fundamental process that plays a crucial role in various aspects of our daily lives and in numerous industries. Understanding how heat moves from one place to another is essential in fields ranging from engineering and physics to environmental science and biology. By studying heat transfer, researchers and engineers can improve the efficiency of systems, design better technologies, and address challenges related to energy transfer and thermal management. This introduction sets the stage for exploring the diverse and fascinating world of heat transfer.[1]

## II.2 Concept of heat

Heat is a specific type of energy produced by the body. Equality of heat and work is a fundamental principle in thermodynamics. Thus, the joule serves as the unit for all quantities of energy, work, and heat.

The study of thermal transfers is based on the ideas of temperature differential and heat amount.

Heat is transferred from one area of a material to another or from one body to another. The body uses kinetic energy for disordered molecular agitation.

This transmission is caused by a temperature differential between the two bodies. The body with the highest temperature spontaneously transfers heat to the body with the lowest temperature, raising the latter's temperature in the process.

As the volume of both bodies remains constant, the temperature of the latter rises while the temperature of the former decreases.

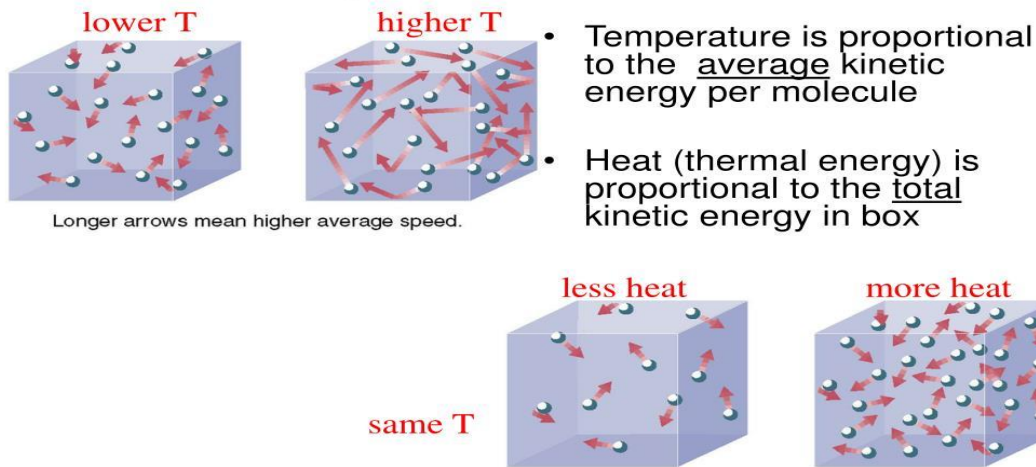
### II.2.1 Concept of temperature

The physical grandeur that gauges a body's or a military's degree of warmth is called temperature.

When two bodies are placed in an adiabatic enclosure, the body that is the hottest dies of the heat to the coldest body, until the two bodies reach the same temperature. It is then said that thermal equilibrium has been reached. **(Fig. 1.1)**

Temperature is a thermodynamic property of the body that gauges the material's microscopical agitation. According to chemical theory, a body's temperature depends on the molecular translation energy of its constituents **(Figure 1.1)**. A body's chemical energy is zero at a temperature known as zero absolute.[2]

## Temperature vs. Heat



**Figure II.1:** Illustration of the concepts of heat transfer, temperature, and thermal balance [3].

### II.2.2. Heat units:

It is known that the quantity of heat in a body is expressed in joules (J), which are the same units as energy and work. Also used is the calorie (Cal), which is defined as the amount of heat required to raise the temperature of 1 gram of water from 14.5 °C to 15.5 °C at 1 atm of pressure. The mechanical work required to produce one calorie is referred to as "the equivalent mechanical of the calorie", and mechanical energy can be converted into thermal energy by freezing. 1 Cal = 4,1855 J [1].

### II.2.3. Heat transfer

The processes by which energy is transferred in the form of heat between bodies or environments at different temperatures  $T_1$  and  $T_2$  are referred to as heat transfers. Heat can be transferred by radiation, convection, or conduction. Even though the three Although processes may occur simultaneously, one mechanism is typically more prevalent. For instance, heat is primarily transferred by conduction through a home's brick walls; water in a casserole set on a cooktop is primarily heated by convection; and the Terre receives a large portion of its heat from the Sun through radiation. The flux generated during the transfer is proportional to the temperature differential between  $T_1$  and  $T_2$  as well as the flux's passage section  $S$ :

$$\mathbf{F} = \mathbf{h} \mathbf{S} (\mathbf{T}_1 - \mathbf{T}_2) \quad (\text{II. 1})$$

$h$  is interpreted as a heat transfer coefficient.

However, this relationship is only valid to the first order, because the coefficient  $h$  most often depends on temperature. We will often introduce the quantity  $F / S$ , which is the flux density, and which is expressed in  $W/m^2$ . The different modes of heat transfer will be studied in detail in the remainder of this course. The problem will be to determine the coefficient  $h$  in each of the modes considered below.[2]

### II.3 Heat transfer mechanisms

Conduction, action in solids, convection requiring cooling, and radiation are the three main types of thermal transport that are often identified.

wherein thermal energy is converted to electromagnetic radiation.

Rarely do these transmission modalities exist exclusively inside a single system.

Nonetheless, one of them is frequently dominating. [1]

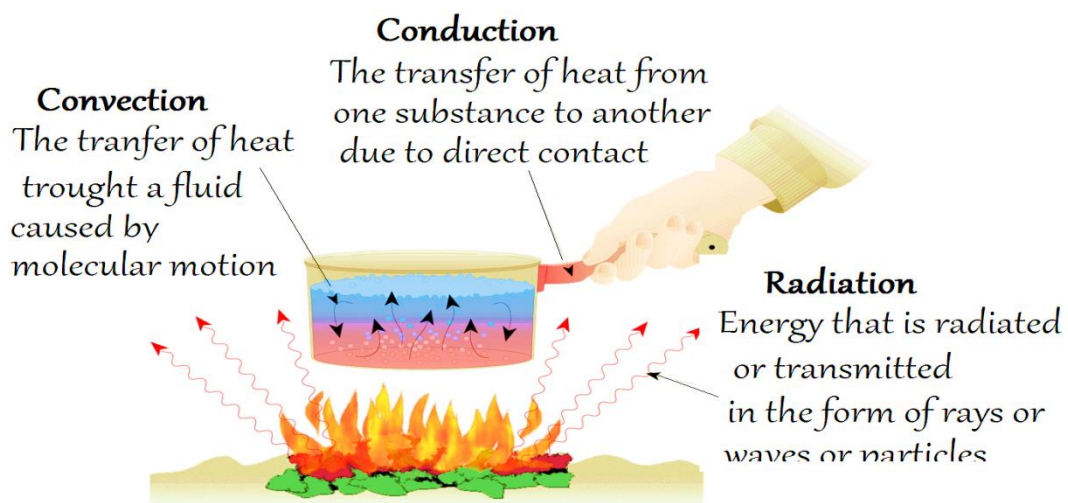


Figure II.2.: illustration of the three modes of heat transfer [4].

#### II.3.1 Heat transfer by conduction:

##### II.3.1.1 Definition:

The phenomenon of heat transfer through one or more solid bodies in direct contact is called conduction. The direction of this heat flow always goes from the hottest element to the coldest. The importance of this flow is directly correlated to the thermal conductivity ( $k$ ) and the temperature difference between the two faces. In mid-season, the interior and exterior temperatures of a home are identical, since there is no temperature difference between the two surfaces, there is no heat conduction. The temperature difference between the interior and exterior faces of the walls is

significant in both winter and summer; consequently, heat moves at varying speeds from the hot point to the cold point

Or in algebraic form:  $\vec{\phi} = -k \text{grade} \bar{T}$  (II. 2)

$$\phi = -kdTdx \quad (\text{II. 3})$$

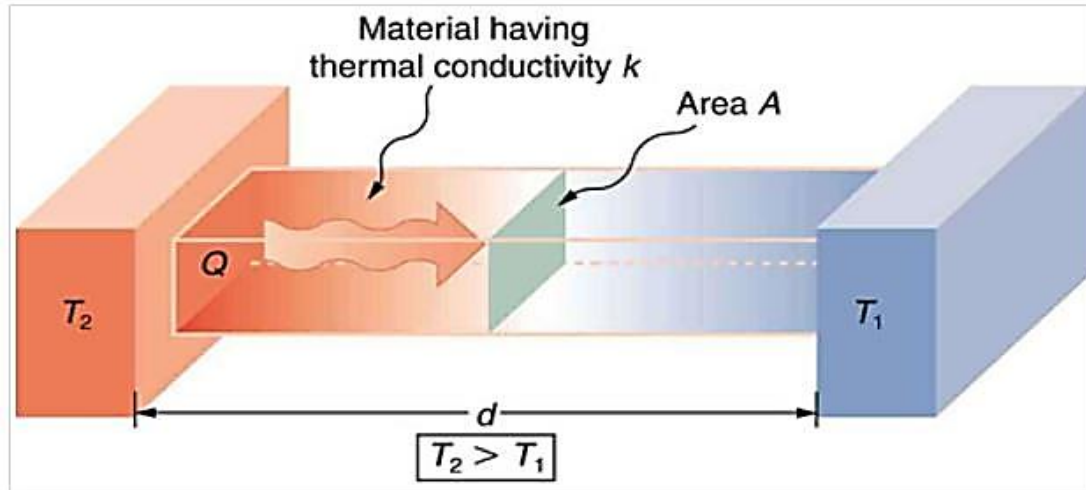


Figure II.3: Heat transfer by conduction [5].

### II.3.1.2. Applications:

The transfer of heat by conduction happens in the spaces between two bodies with different temperatures. This includes the surfaces of heat exchangers, but also the walls and windows of a building, the lids of containers holding hot or cold liquids, the doors of ovens, and so on [12]. It is common for the doors to be made of several materials, each with its own specific function (insulator, anticorrosion coating, heat conductor, etc.), and they are made up of composite doors through which the heat transfer takes place.

### II.3.2 Heat Transfer by Convection:

#### II.3.2.1 Definition:

In fluid mechanics, convection is a transfer of thermal energy that is accompanied by the transport of matter in a fluid state. This fluid can be a gas or a liquid. Convection induces an overall displacement of matter. The movement of matter occurs vertically, from top to bottom or from bottom to top. The denser areas of the fluid descend, while the less dense parts rise. Thermal convection also refers to the heat transfer between a moving fluid and a solid wall. There are two types of convection: natural convection and forced convection.[5]

##### a - Natural convection:

movements are due to variations in density in a fluid subjected to the gravitational field. Variations in density can be generated by temperature gradients (warm air is lighter than cold air) and/or composition gradients (air in a room heated by a radiator, ocean or atmospheric currents, etc.).

##### b- Forced convection:

the movement of the fluid is caused by external mechanical actions (pump, fan, etc.).

##### C- Mixed convection:

Mixed convection corresponds to the coupling of the two previous phenomena (natural and forced convection) when the fictitious flow velocities are due to the two types of convection separately.

#### Newton's law

This transfer mechanism is governed by Newton's law, which states that the density of heat flux exchanged between a solid wall and a flowing fluid is proportional to the temperature difference that gave rise to it; it is given by:

$$T_p > T_\infty$$

$$\phi = h \cdot S \cdot (T_p - T_\infty) \quad (\text{II.4})$$

**h** is a positive quantity called the convective exchange coefficient, in  $(\text{w} \cdot \text{m}^{-2} \cdot \text{k}^{-1})$

**S** is the heat exchange surface.

**T<sub>p</sub>** is the wall temperature.

**T<sub>∞</sub>** is the temperature away from the wall.[5]

#### II.3.2.2. Dimensionless numbers

##### a. Reynolds Number

The forced convection flow regime is characterized by a dimensionless number: the Reynolds number, which quantifies the magnitude of inertial forces relative to viscous forces. It is given by:

$$\mathbf{Re} = \frac{\text{forces d'inerti}}{\text{forces visqueuses}} = \frac{V.L_C}{\nu} = \frac{\rho.V.L_C}{\mu} \quad (\text{II.5})$$

where:  $V$  is the characteristic flow velocity ( $\text{ms}^{-1}$ ).

$L_C$ : is a characteristic length of the system studied (m).

$\nu$ : is the kinematic viscosity of the fluid ( $\text{m}^2/\text{s}$ )

$\mu$ : is the dynamic viscosity of the fluid ( $\text{kg.m}^{-1}.\text{s}^{-1}$ )

$\rho$ : is the density of the fluid ( $\text{kgm}^{-3}$ ) [5]

### b. Grashof Number:

The flow regime under natural convection is characterized by a dimensionless number: the Grashof number, which quantifies the magnitude of Archimedean forces relative to viscous forces. It is given by:

$$\mathbf{Gr} = \frac{\text{forces d'Archimed?}}{\text{forces visqueuse?}} = \frac{g.\beta.\Delta T.L_C^3}{\nu^2} \quad (\text{II.6})$$

where:  $g$  is the acceleration due to gravity ( $\text{m.s}^{-1}$ ).

$\beta$  is the coefficient of thermal expansion ( $\text{K}^{-1}$ )  $\beta = \frac{1}{\rho} \left( \frac{\partial \rho}{\partial T} \right)_p$

$\Delta T$  is a temperature difference characteristic of the system studied (K).

$L_C$  is a characteristic length of the system studied (m).

$\nu$  is the kinematic viscosity of the fluid ( $\text{m}^2/\text{s}$ )

### c. Prandtl Number:

The behavior of the fluid with respect to convective heat exchange is characterized by the Prandtl number, which quantifies the magnitude of momentum diffusivity relative to thermal diffusivity. It is given by:

$$\mathbf{Pr} = \frac{\text{diffusivité de quantité mouvemen}}{\text{diffusivité thermiqu}} = \frac{\nu}{\alpha} \quad (\text{II.7})$$

is the thermal diffusivity of the fluid  $\text{m}^2/\text{s}$  defined by:  $\alpha = \frac{\lambda}{\rho.c_p}$

Where  $\lambda$  is the thermal conductivity of the fluid ( $\text{W.m}^{-1}.\text{K}^{-1}$ )

$C_p$  is the specific heat of the fluid ( $\text{J.kg}^{-1}.\text{K}^{-1}$ )

$N$  is the specific heat of the fluid ( $\text{m}^2/\text{s}$ )

$\rho$  is the density of the fluid ( $\text{kg.m}^{-3}$ )

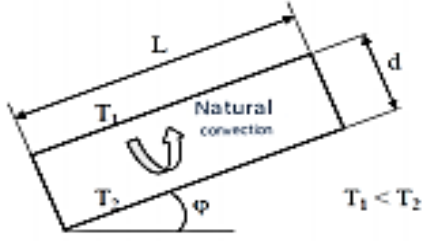
### d. Nusselt Number:

The Nusselt number quantifies the magnitude of convection heat flow relative to conduction heat flow. It is given by:

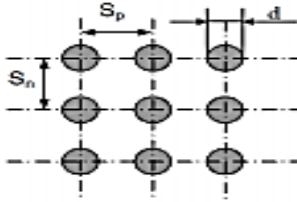
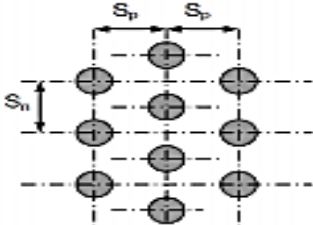
$$\frac{\text{flux convecti}}{\text{flux conducti}} = \frac{h.Lc}{\lambda} \quad (\text{II.8})$$

A local Nusselt number can also be defined from the local heat exchange coefficient associated with the heat flux exchanged locally between a wall and the fluid, or an average Nusselt number

defined from the average heat exchange coefficient associated with the overall heat flux over the entire surface of the wall [5].

Valid correlations for all fluids: $Nu = C (Gr Pr)^m$			
Geometry	$Gr Pr$	$C$	$m$
Plates and vertical cylinders	$10^4 - 10^9$ $10^9 - 10^{13}$	0.59 0.021	1/4 2/5
Horizontal cylinders	$10^{-10} - 10^{-2}$	0.675	0.058
	$10^{-2} - 10^2$	1.02	0.148
	$10^2 - 10^4$	0.850	0.188
	$10^4 - 10^7$ $10^7 - 10^{12}$	0.480 0.125	0.25 0.33
Upper face of a hot plaque or lower face of a cold plaque	$2 \cdot 10^4 - 8 \cdot 10^6$ $8 \cdot 10^6 - 10^{11}$	0.54 0.15	0.25 0.33
Lower face of a hot plaque or upper face of a cold plaque	$10^5 - 10^{11}$	0.27	0.25
Inclined rectangular firm cell 	$Nu = 1 + 1.44 \left[ 1 - \frac{1708}{Gr Pr \cos \varphi} \right] \left[ 1 + \frac{1708 (\sin(1.8) 1.6) + \left[ \left( \frac{Gr Pr \cos \varphi}{5830} \right)^{1/3} - 1 \right]}{Gr Pr \cos \varphi} \right]$ $Nu = \left( \frac{Gr Pr \cos \varphi}{5830} \right)^{1/3} - 1 \quad \text{si } 0 < \varphi < \varphi^*$ $Nu = (\sin \varphi)^{1/4} Nu(90^\circ) \quad \text{si } \varphi^* < \varphi < 90^\circ$ $Nu = 1 + [Nu(90^\circ) - 1] \sin \varphi \quad \text{si } 90^\circ < \varphi < 180^\circ$ <p style="text-align: center;">With <math>p = \tan^{-1}(4800 Pr)</math></p>		
Simple air to atmospheric pressure relationships			
Geometry	Laminar $10^4 < Gr Pr < 10^6$	Turbulent $Gr Pr > 10^9$	
Vertical plate or cylinder	$1/4 h = 1.42 \left( \frac{\Delta \theta}{L} \right)$	$h = 1.31 (10)^{-3}$	
Horizontal cylinder	$h = 1.32 \left( \frac{\Delta \theta}{d} \right)^{1/4}$	$h = 1.24 (40)^{-3}$	
Upper face of a hot horizontal plate or lower face of a cold plate	$h = 1.32 \left( \frac{\Delta \theta}{L} \right)^{1/4}$	$h = 1.52 (10)^{-3}$	
Lower face of a hot plate or upper face of a cold plate	$1/4 h = 0.59 \left( \frac{\Delta \theta}{L} \right)$	$h = 0.59 L \left( \frac{\Delta \theta}{L} \right)^{1/4}$	

**Table II.1:** Correlations for calculating forced convection transfer coefficients [5].

Géométrie	Corrélation										
Ecoulement perpendiculaire à un faisceau de 10 tubes	$Nu = C Re^n Pr^{1/3}$ , vitesse $u_x$ calculée en amont du tube										
		$\frac{S_n}{d}$									
	$\frac{S_p}{d}$	1,25		1,5		2,0		3,0			
		C	n	C	n	C	n	C	n		
		Disposition en ligne									
	1,25	0,38 6	0,592	0,305	0,608	0,111	0,704	0,070	0,752		
	1,5	0,407	0,586	0,278	0,620	0,112	0,702	0,075	0,744		
	2,0	0,464	0,570	0,332	0,602	0,254	0,632	0,220	0,648		
	3,0	0,322	0,601	0,356	0,584	0,415	0,581	0,317	0,608		
		Disposition en quinconce									
	$\frac{\phi}{\delta}$	-	-	-	-	-	-	0,236	0,636		
	0,9	-	-	-	-	0,495	0,571	0,445	0,581		
	1,0	-	-	0,552	0,558	-	-	-	-		
	1,125	-	-	-	-	0,531	0,565	0,575	0,560		
1,25	0,575	0,556	0,561	0,554	0,576	0,556	0,579	0,562			
1,5	0,501	0,568	0,511	0,562	0,502	0,568	0,542	0,568			
											
	Disposition en ligne				Disposition en quinconce						
Ecoulement perpendiculaire à un faisceau de n rangées de tubes (n ≤ 10)	$N = \frac{h_a}{h_{10}}$										
	Nombre rangées	1	2	3	4	5	6	7	8	9	10
	N en ligne	0,64	0,80	0,87	0,90	0,92	0,94	0,96	0,98	0,99	1,0
	N en quinconce	0,68	0,75	0,83	0,89	0,92	0,95	0,97	0,98	0,99	1,0

**Table II.2:** Correlations for the calculation of convection transfer coefficients forced.

### II.3.2.3 Applications:

Infrared radiation is used in numerous industrial processes. Its action on materials is primarily thermal, and the main applications related to this radiation are:

- Drying (paper, cardboard, textiles, etc.);
- Cooking (dyes, finishes, coatings, etc.);
- Heating (before forming various materials, heat treatments, welding, heating workstations, etc.);
- Polymerization (inks, coatings, packaging, etc.);
- Sterilization (pharmaceutical bottles, various food products, etc.);

Ultraviolet radiation consists of photons whose energy is of the order of magnitude equal to the energy of atomic bonds. These photons act on materials by shifting electrons to higher energy levels. When the material exposed to the radiation is sensitive to it, chemical reactions occur. The portion of ultraviolet radiation absorbed by the material and not used in the

chemical reaction is transformed into heat. In practice, this heating remains low, and ultraviolet radiation is mainly used in the crosslinking of plastic films and the polymerization of organic products such as printing inks, lacquers, and varnishes, operations that are often incorrectly called drying.[6]

### II.3.3. Heat Transfer by Radiation:

#### II.3.3.1. Definition:

Radiation is a heat transfer that does not require a material medium, unlike the other two. Indeed, this type of heat transfer results from the emission of electromagnetic rays that carry energy. They are emitted by a hot body, such as the sun, and heat the body that receives them [7].

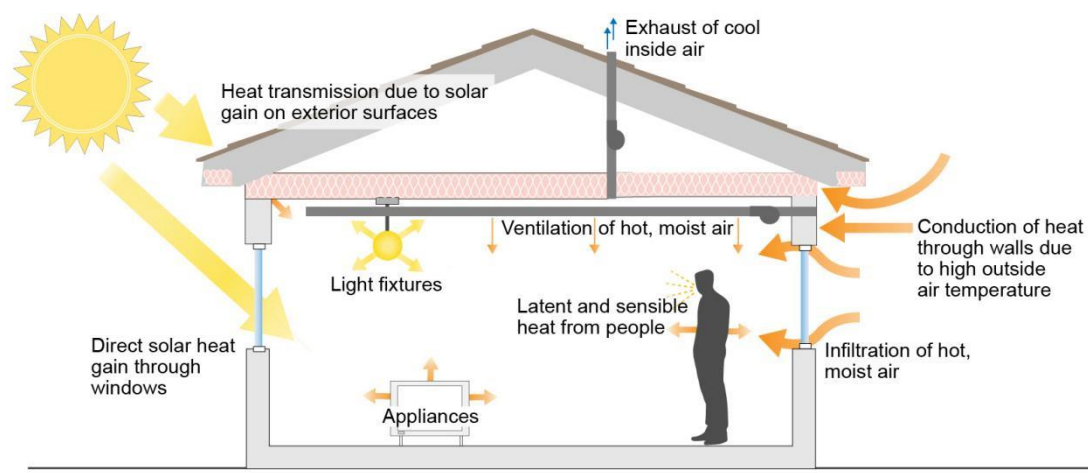


Figure II.4: Heat transfer by radiation [8].

The basic equation used to express radiation is STEFAN BOLTZMANN's law

$$\dot{Q} = \sigma \epsilon S T^4 \quad (\text{II.9})$$

$\dot{Q}$  : Quantity of heat exchanged

$\sigma$  : Constant of STEFAN BOLTZMANN

$\epsilon$  : Thermal emissivity of the material

S: Exchange surface

T: Temperature.

#### II.3.3.2. Applications:

The applications of convection heat transfer are far too numerous

To list them all. They occur whenever a liquid or gas is heated or cooled, whether it be boiling water in a saucepan, a central heating radiator, a radiator associated with a car engine, or a heat exchanger in a process, such as an evaporator or condenser. Convection applies

Even if the heat exchange surface is not formed by a wall, which is the case with mixed condensers or atmospheric refrigerants, or even hot air dryers [1].

### II.3.4.1 Laminar and turbulent boundary layers

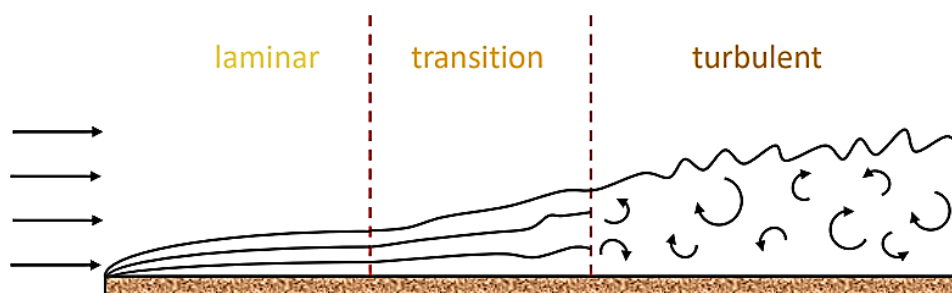
#### II.3.4.2. Introduction:

Joseph Black's centuries-old description of heat convection sounds odd to our ears. Yet it is surprisingly accurate. Cold air really does sweep away warm air that is "entangled" with a warm body. Cold air really does replace warm air. What Black called "entanglement" is a fluid-mechanical process that we must deal with before we can analyze convective heating and cooling

#### II.3.4.3 General Boundary Layer Concepts •

Let's look at a viscous flow over a flat plate.

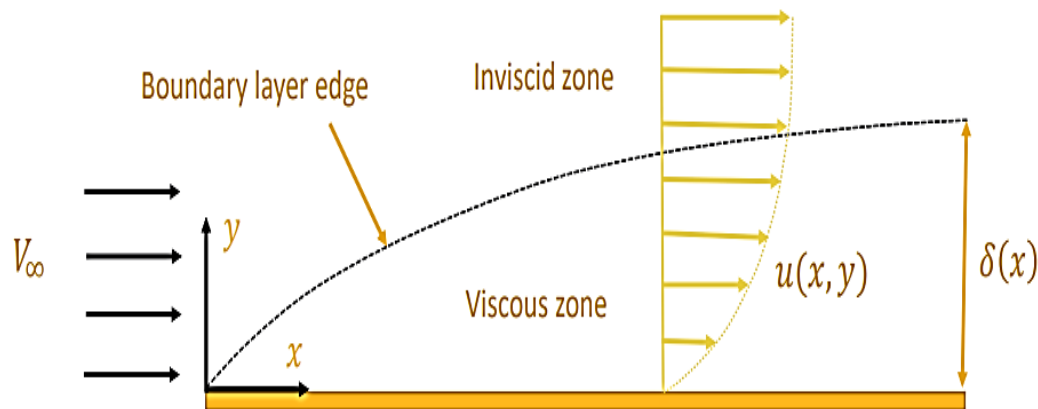
- The boundary layer forms at the leading edge of the plate and increases in thickness from the leading edge. We denote the local boundary layer thickness by  $\delta(x)$ .
- The flow is initially laminar. As it proceeds along the plate, the laminar flow will begin to break down (within the transition region) and finally become fully turbulent.



**Figure II.5:** A boundary layer of thickness  $\delta$ .

- The boundary layer idea assumes that the fluid transitions from a velocity of zero at the wall (no slip) to the free stream velocity away from the wall, denoted  $V_\infty$ .
- The boundary layer thickness  $\delta(x)$  is defined rigorously as the distance away from the surface where the fluid velocity  $u(x,y)$  reaches 99% of the free-stream velocity. Experimentally, it is found to grow proportionately to the distance from the leading edge of

the plate. This growth rate is also a function of the Reynolds number and depends on the flow regime (laminar or turbulent).



**Figure II.6** Steady-state boundary layer model for flow over a flat plate.

#### II.3.4.4. Laminar Boundary Layer

- The boundary layer will, in general, be laminar in the range of Reynolds numbers: This range, however, is merely an order of magnitude guidance, as the transition to turbulence depends on many factors, such as free-stream conditions and surface roughness, and it may occur at lower or higher Reynolds numbers.
- A boundary layer is not always present along the entire length of a wall of a bluff body. There are no boundary layers in the separated regions downstream of the bodies.
- While the boundary layer theory cannot describe separated flow, it can, in fact, predict the point of separation.  $1000 < Re_L < 10^6$  Boundary Layer separation on a bluff body. Bluff Body Flow.

#### II.3.4.5 Turbulent Flow

Turbulent flow is marked by chaotic and irregular movement of fluid particles, leading to the formation of vortices and complex interactions.

##### II.3.4.5.1. Characteristics:

- High Reynolds number (typically greater than 4000).
- Occurs in systems with high flow rates or in the presence of obstacles.
- Results in increased friction and energy loss

##### II.3.4.5.2 Applications

Laminar flow is often desirable in applications requiring precise control, such as in microfluidics, where small volumes and minimal mixing are crucial.

Turbulent flow is common in industrial processes, cooling systems, and environmental engineering, where efficient heat transfer is necessary.

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[2] Dr Lyes Bordja UNIVERSITE L'ARBI BEN M'HIDI

[3]

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[4] <https://pbs.twimg.com/media/Dyz4ebRUcAAS397.jpg>.

[5] <https://scx2.b-cdn.net/gfx/news/2014/1-whatishheatco.jpg>.

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[8]

<https://th.bing.com/th/id/OIP.dNSKMeX0w3ezgn8rGTjUgHaDP?w=1634&h=715&rs=1&pi=ImgDetMain>.

**Chapter III**  
**Numerical methods for**  
**solid-liquid phase-change**  
**problems**

### **III.1. Introduction:**

Theoretical modeling of solid-liquid phase change processes is of much interest in energy storage and thermal management. While most theoretical phase change models assume that the phase change material (PCM) is in direct contact with the thermal source/sink, in most practical scenarios, the two are separated by a thick wall, which, in some cases, may comprise multiple heterogeneous layers. Accounting for thermal conduction through the multi-layer wall is important to ensure accuracy of the predicted phase change characteristics. This paper presents theoretical analysis of phase change in a system comprising a PCM and a multi-layer Cartesian wall using the eigenfunction expansion method and analysis of multi-layer thermal conduction. Thermal contact resistance between wall layers, and between the wall and PCM are accounted for. The predicted phase change front propagation is shown to agree well with past work for special cases of a homogeneous wall, as well as with numerical simulations. Two distinct timescales in the solution, related to diffusion through the wall and phase change propagation in the PCM are identified. The impact of the imposed temperature, wall thermal diffusivity and thickness are presented in non-dimensional forms. Practical problems related to design of a PCM wall for energy storage are solved, as well as the impact of wall thickness on phase change propagation. The results presented here improve the fundamental understanding of phase change heat transfer processes, and are particularly relevant for relatively thick, thermally insulating walls over relatively short time periods, for which a resistance approximation for the wall is not accurate.

In this chapter, we present the phase change phenomenon and the mathematical model for simulating thermal behavior in both conductive and convective modes across a cavity containing the PCM. We express the conservation equations of mass, momentum, and energy, as well as the solidification theory and methods for analyzing phase change flows. [1]

### **III.2. Solidification theory:**

Solidification is widely considered in literature to be a Stefan problem. This name was given following the work of the famous researcher Stefan, who studied the problem of melting and freezing of water in 1890. This was the first work to model the liquid/solid phase change phenomenon. Generally, there are two approaches to analyzing phase change problems: the time-moving mesh method and the fixed mesh method.

### III.2.1 The Stefan problem:

The release or absorption of latent heat during solidification or melting transformations characterizes the phase change. At the interface, there is a sudden change in the specific enthalpy "H". When the phase change is isothermal, the problem is called the Stefan problem. Its resolution consists of modeling the heat transfer in each phase with a coupling at the interface.

### III.2.2 Two-Phase Stefan Problem

The formulation of the Stefan problem is deduced from the conservation of energy expressed separately for the solid and liquid phases with interface coupling. The equations to be solved in the two phases according to [III.2] are, respectively, for the solid and liquid phases:

$$(\rho c)_s \frac{\partial T_s}{\partial t} = \nabla(\lambda_s T_s) \quad (\text{III.1})$$

$$(\rho c)_l \frac{\partial T_l}{\partial t} = \nabla(\lambda_l T_l) \quad (\text{III.2})$$

Where  $\rho$  is the density,  $C$  is the specific heat, and  $\lambda$  is the thermal conductivity of the material.

The heat balance at the interface where the two temperature fields are linked by the energy balance condition is defined by the expression

$$\rho L \frac{d_s}{dt} = \left[ \lambda \frac{\partial T}{\partial n} \right]_s - \left[ \lambda \frac{\partial T}{\partial n} \right]_l \quad (\text{III.3})$$

This equation expresses the release or absorption of latent heat due to phase change.

Where  $T$  is the phase change temperature  $T_f$ ,  $L$  is the latent heat of the phase change,  $n$  is the local normal directed outward from the solid domain.  $\frac{\partial T}{\partial n}$  the local normal velocity of the solid/liquid interface. Note that in the case where heat transfer in the liquid phase is purely conductive, the problem is a two-phase Stefan problem. It is necessary to solve the three energy equations indicated above simultaneously.

### III.2.3. Methods for analysing flows with phase change:

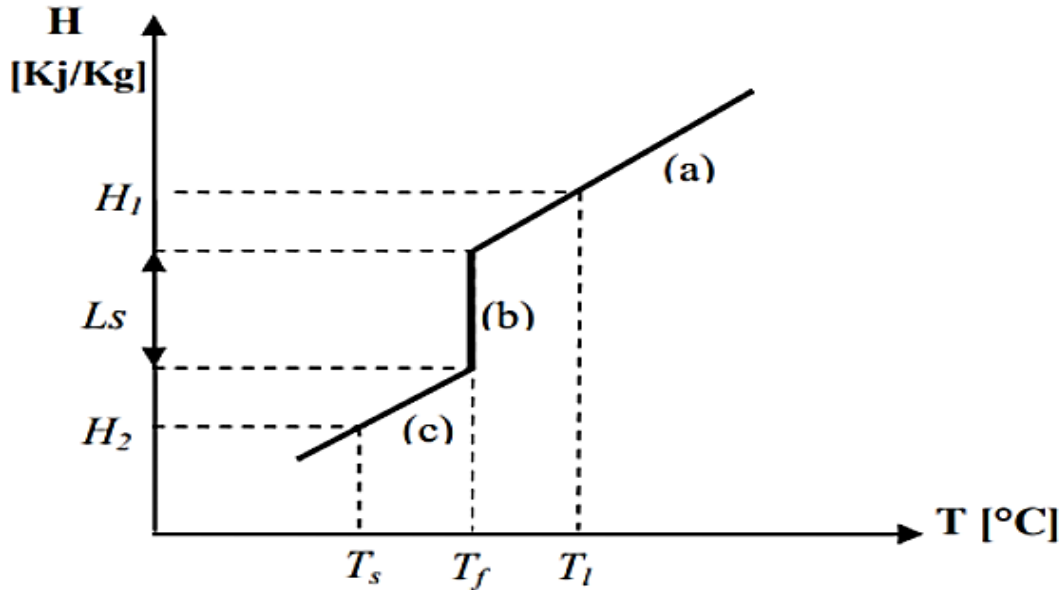
Consider a pure metal in a molten state at a temperature  $T_l$  above the melting temperature.

During solidification, the temperature gradually decreases following plateau (a), then stabilizes

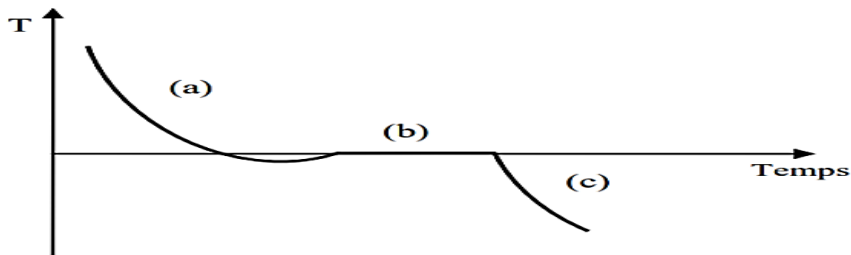
during the phase change at temperature  $T_f$  following plateau (b), in which the metal is partially solidified. The metal continues to cool and moves from temperature  $T_f$  to temperature

At following plateau (c), where it will be completely solidified. Here, the liquid-to-solid phase changes

(solidification) and solid-to-liquid (melting) at a given temperature are considered, see the representation in Fig. III.1. (a) and (b). [2]



**Fig. III.1:** Representation of enthalpy as a function of temperature



**Fig. III.2:** Slow cooling curve of a pure metal as a function of time

Each step represents a specific state of the metal, and the enthalpy change in each step is given as follows:

$$\begin{aligned}
 \text{Palier (a)} &: dH = C_{pl} dT \quad \text{pour } T > T_f \\
 \text{Palier (b)} &: dH = L_s \quad \text{pour } T = T_f \\
 \text{Palier (c)} &: dH = C_{ps} dT \quad \text{pour } T < T_f
 \end{aligned}
 \tag{III.4}$$

H is a discontinuous function at  $T = T_f$ . This discontinuity marks the separation between the liquid and the solid and is called a two-phase interface. For the metal to completely solidify, the following amount of energy  $\Delta H$  must be removed from it:

$$\Delta H = C_{pl} (T_l - T_f) + L_s + C_{ps} (T_l - T_s) \quad (\text{III. 5})$$

With:

$T_l$  : Refers to the temperature of the metal in the liquid state

$T_s$ : Refers to the temperature of the metal in the solid state

$T_f$  : Désigne la température de solidification (fusion)

$C_{pl}$  and  $C_{ps}$  are the thermal capacities of the liquid and the solid, represented by the slopes of the levels (a) and (b) on the graph.

In its liquid form, the metal has the latent heat  $L_s$  per unit mass plus the sensible heat represented by the relationship:

$$C_{pl} (T_l - T_f) \quad (\text{III. 6})$$

For a pure metal, enthalpy is related to temperature by:

$$\Delta H = \begin{cases} C_{pl} \Delta T + L_s & \text{pour } T > T_f \\ C_{ps} \Delta T & \text{pour } T < T_f \end{cases} \quad (\text{III. 7})$$

For an alloy, where solidification takes place across a solidification interval ( $T_l - T_s$ ), the enthalpy is related to the temperature by:  $f_l$  denotes the liquid fraction.

$$\Delta H = \begin{cases} C_{pl} \Delta T + L_s & \text{pour } T \geq T_f \\ C_{pl} \Delta T + f_l L_s & \text{pour } T_s < T < T_l \\ C_{ps} \Delta T & \text{pour } T \leq T_f \end{cases} \quad (\text{III. 8})$$

In the solidification or melting process, the temperature changes in each phase and the two-phase interfaces shift. The term "multiple two-phase interfaces" is used here because it suggests that there are multiple solidification and melting fronts. Subsequently, the presence of a single front, although several fronts may be present. The shift of the two-phase interface cannot be tracked by considering only the temperature change for certain points in the domain, since heat transmission depends on the displacement of the interface and vice versa. [3]

### III.3. Numerical Methods:

Multiple analytical solutions are considered to address the most common cases of phase change problems, with simplifying assumptions such as constant thermophysical properties in each phase, simple geometries, etc. These solutions are no longer sufficient when addressing

more complex problems. Indeed, the analytical solutions in the literature apply when the medium is considered semi-infinite. The case of phase change in finite media requires the use of numerical calculations. To this end, two main classes of solutions have been considered to numerically resolve phase change phenomena

### III.3.1 Moving Mesh Method:

In this method, the conservation equations are written in terms of temperature in each phase. They are solved separately in the liquid and solid regions. The position of the interface is obtained by solving the balance equation at the interface (Stefan condition).

The equations governing heat transfer are:

Liquid region:

$$cp_l \rho_l \left( \frac{\partial T}{\partial t} + u \frac{\partial T}{\partial x} + v \frac{\partial T}{\partial y} \right) = \lambda_l \frac{\partial^2 T}{\partial x^2} + v \frac{\partial^2 T}{\partial y^2} \quad (\text{III. 9})$$

$$cp_s \rho_s \left( \frac{\partial T}{\partial t} + u \frac{\partial T}{\partial x} + v \frac{\partial T}{\partial y} \right) = \lambda_s \frac{\partial^2 T}{\partial x^2} + v \frac{\partial^2 T}{\partial y^2} \quad (\text{III. 10})$$

At the liquid-solid interface, the two equations (III.6) and (III.7) are coupled by the Stefan condition

$$\begin{cases} T^l = T_s = T_f \\ -\lambda_s \frac{\partial T_s}{\partial n} + \lambda_s \frac{\partial T_l}{\partial n} = \rho_s L_s \frac{\partial \xi}{\partial n} \end{cases} \quad (\text{III. 11})$$

$n$  denotes the normal to the front and  $\xi$  the position of the solidification front. The Stefan condition (III.8) reflects the system's enthalpy drop (releasing latent heat  $L_s$ ) at the melting temperature  $T_f$ . This approach is suitable for pure metals where the phase change occurs at a constant temperature. Generally, analytical solutions for Stefan models remain very limited for 1D cases with constant boundary conditions and thermophysical properties. In practical situations, boundary conditions and thermophysical properties are variable and multiple, and geometries are multi-dimensional and irregular, requiring powerful numerical techniques to study them. [4]

### III.3.2 Fixed-mesh method:

In these methods, a single energy equation is applicable in both phases, and therefore it is not necessary to consider the liquid and solid phases separately. During the calculation, the mesh remains fixed, and the equations governing heat transfer in the liquid and solid regions are solved simultaneously, despite the discontinuity in the temperature gradient at the interface. The advantage of these methods lies in their simplicity and ease of implementation, even in the three-

dimensional case. Within this family of methods, the two most widely used methods are the effective (apparent) capacity method and the enthalpy method. [5]

### III.3.2 .1. Effective capacity method:

The effective capacity method introduces the effect of latent heat on the material's heat capacity in a small temperature range near the melting temperature (phase change). Overall, this method is quite simple but less precise than fixed-mesh methods. [III.3-III.4-III.5-III.6] The energy equation:

$$\rho C_{\text{eff}} \left( \frac{\partial T}{\partial t} + u \frac{\partial T}{\partial x} + v \frac{\partial T}{\partial y} \right) = \lambda \frac{\partial^2 T}{\partial x^2} + \nu \frac{\partial^2 T}{\partial y^2} \quad (\text{III. 12})$$

With:

$$C_{\text{eff}} = \begin{cases} C_{ps} & \text{si } T < T_f \\ \frac{L_s}{T_l - T_s} & \delta(T - T_f) \\ C_{pl} & \text{si } T > T_f \end{cases} \quad \text{si } T = T_f \quad (\text{III. 13})$$

Type equation here.

Where  $\delta(T - T_f)$  represents the Dirac function, which is infinite at  $T = T_f$  and zero elsewhere. It satisfies the following equation:

$$\int_{-\infty}^{+\infty} \delta(T - T_f) = 1$$

To facilitate the numerical calculation, the Delta function is introduced to locate the nodes where the latent heat is included in the specific heat, which gives (Fig. III.3)

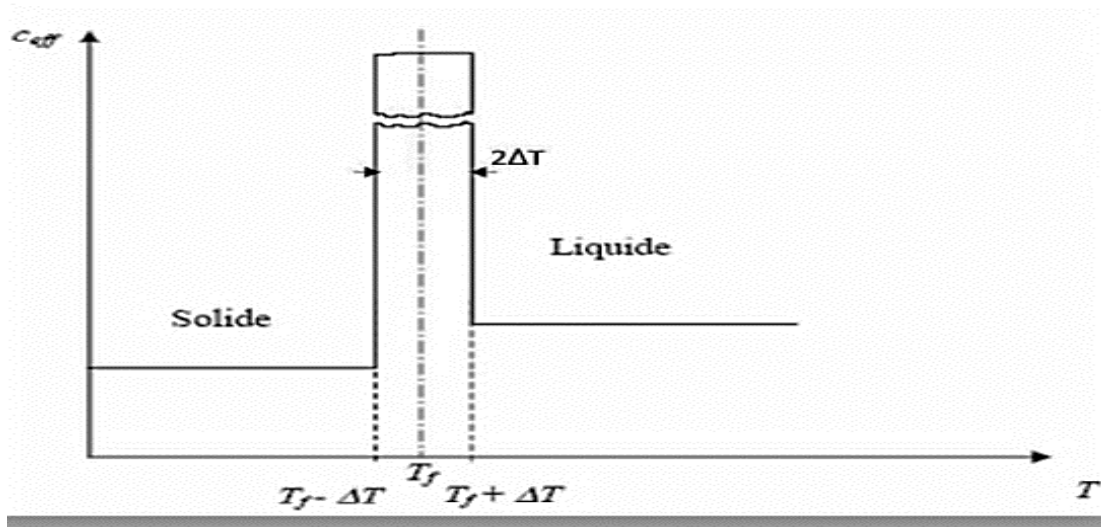
$$C_{\text{eff}} = \begin{cases} C_{ps} & \text{pour } T < T_f - \Delta T \\ C_p + \frac{L_s}{2\Delta T} & \text{pour } T_f - \Delta T \leq T \leq T_f + \Delta T \\ C_{pl} & \text{pour } T > T_f + \Delta T \end{cases} \quad (\text{III. 14})$$

For

alloys, the  $2\Delta T$  interval is  $T_l - T_s$

For pure metals, the phase change

completes at a constant temperature, and the interval should be as small as possible.



**Figure III.3:** Heat capacity including the effect of latent heat in a small interval  $2\Delta T$  in the vicinity of  $T_f$ .

### III.3.2 .2 Enthalpy method

A simple and widely applicable fixed-domain method for solving the convection/diffusion phase-change problem is the enthalpy method proposed by Voller and Cross [6]. The essential feature of this formulation is that it tracks the moving front in an implicit manner by iso-lating latent heat effects in a source/sink term. Therefore, a difficulty arises in accounting for mass and heat transfer conditions near the interface. A common approach to overcome this difficulty is to define appropriate volume source terms in governing equations [7]. More specifically, in the energy equation latent heat is considered by assigning a latent heat value to each computational cell according to the cell temperature. The governing energy equation of the enthalpy method is as follows:

$$\frac{\partial}{\partial t} \rho H + \frac{\partial}{\partial x_i} (\rho u_i) = \frac{\partial}{\partial x_i} \left( k \frac{\partial T}{\partial x_i} \right) \quad (\text{III. 15})$$

where  $H$  is the specific enthalpy, which is defined in each control volume as the sum of sensible enthalpy ( $h$ ) and latent heat ( $\Delta H$ ):

$$H = h + \Delta H \quad (\text{III. 16})$$

Sensible enthalpy  $h$  is equal to:

$$h = h_{\text{ref}} + \int_{T_{\text{ref}}}^T c_p dT \quad (\text{III. 17})$$

where  $h_{\text{ref}}$  is the enthalpy at the reference temperature ( $T_{\text{ref}} = 25^\circ \text{C}$ ).

Eq. (III. 15) contains the source term  $S_h$  used in basic formulation of the enthalpy method defined as:

$$S_h = \frac{\partial(\rho\Delta H)}{\partial t} + \frac{\partial}{\partial x_i}(\rho u_i \Delta H) \quad (\text{III. 18})$$

Ultra-High Temperature Thermal Energy Storage, Transfer and Conversion

In the enthalpy method, latent heat is a function of temperature:

$$\Delta H = f(T) \quad (\text{III. 19})$$

This method presents several advantages: (1) it is valid for a wide range of cases where PCM melts, either at a single temperature point or over a temperature range, (2) enthalpy formulation and velocity correction schemes are independent of the used numerical technique (FEM, FDM, and FVM), (3) the governing energy equation is similar to the single phase equation, and (4) there is no condition to be satisfied at the solid liquid interface as it automatically obeys the interface condition. Additionally, it is simple and accurate method: it has been validated by many researchers against experimental data [7,8,9].

Due to its numerous advantages, it is one of the most popular methods for solidification melting problems.

The flow field is solved by either using N-S equations or by means of the Lattice Boltzmann method. For the first approach, the following equations are solved:

Continuity equation

$$\frac{\partial u_i}{\partial x_i} = 0 \quad (\text{III. 20})$$

Momentum equation

$$\frac{\partial}{\partial t}(\rho u_i) + \frac{\partial}{\partial x_i}(\rho u_i u_i) + \mu \frac{\partial^2 u_i}{\partial x_j \partial x_j} + \rho g_i \quad (\text{III. 21})$$

The details regarding the solution of the flow field with Lattice Boltzmann method and its coupling with the enthalpy method can be found in the study of Fuentes et al.

### III.3.2 .3 Enthalpy-porosity method:

The enthalpy-porosity method has been widely used to investigate solidification melting in which natural convection is significant. The two main advantages of this method are its fast convergence and high accuracy. It is a leading tool today for modeling solid liquid phase-change

processes. Assis et al. [10,9] successfully validated this method against experimental predictions.

### Analytical equations

In the enthalpy-porosity model, latent heat is given by the following equation:

$$\Delta H = \beta L \quad (III. 22)$$

where  $\beta$  is the liquid fraction defined as:

$$\beta = \begin{cases} 0 & \text{if } T < T_{\text{solidus}} \\ \frac{T - T_{\text{solidus}}}{T_{\text{liquidus}} - T_{\text{solidus}}} & \text{if } T_{\text{solidus}} < T < T_{\text{liquidus}} \\ 1 & \text{if } T > T_{\text{liquidus}} \end{cases} \quad (III. 23)$$

Thus, latent heat varies between zero (solid phase) and  $L$  (liquid phase). Two important issues that need special attention in this method are the density variation and solids

### PCM density variation and natural convection

The presence of density changes between phases might affect the PCM structure but not so much the heat transfer process [11]. Situations where density differences are present between phases or where density variations occur in a liquid are handled by different approaches.

**Boussinesq approximation** With the Boussinesq approximation, the density changes in PCM is considered only in the buoyancy term of the momentum Eq. (III. 21).

$$\rho = \rho_0(1 - \beta_{\text{th}}\Delta T) \quad (III. 24)$$

where  $\Delta T$  is the difference between the cell temperature and reference temperature,  $T_0$ , at which the reference density,  $\rho_0$ , is measured.

The Boussinesq approximation with the enthalpy-porosity approach has been widely used in the literature to simulate the effect of natural convection in the thermal performance of various PCMs [12,13].

**Density changes during phase change** Most numerical methods found in the literature for Solving the solid liquid phase change assumes a constant density upon melting or solidification or in best cases a density variation with the Boussinesq approximation or ETC.

However, those methods are not efficient when applied to the phase change with volume expansion or shrinkage. A more accurate approach is to consider the density change in

the two different phases and a linear interpolation in the mushy zone to avoid numerical instabilities.

$$\rho_s \quad T < T_s$$

$$\rho_{pcm} = \text{Linear variation } T_s < T < T_l$$

$$\rho_l \quad T < T_l$$

## Conclusion

In this chapter, we reviewed a variety of numerical methods used to study phase change phenomena. These methods are characterized by their diversity and capability to address the challenges associated with the irregular shape of the region of interest, necessitating accurate models to predict material behavior.

We applied several techniques, including finite element methods, which demonstrated their effectiveness in simulating thermal changes in materials. Additionally, we discussed the importance of selecting the appropriate method based on the characteristics of the system being studied and the requirements for accuracy.

These findings are essential for developing more precise models that can be applied in practical applications, such as energy storage, where understanding the dynamics of phase change is crucial for improving the thermal performance of systems.

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# ***CHAPTER IV***

## ***RESULTS AND DISCUSSIONS***

## IV.1 Introduction

Improvement of heat storage efficiency of thermal system has been necessary to maximize the potential of combined heat and power generation or renewable energy sources for heating and cooling. Using a phase change material (PCM) could be an attractive choice in many instances array. Commercially available PCMs were investigated using T-history method with adequate agreement with the data from the company. The produced LHTES with cylindrical capsules is easier in capacity, charging/discharging time, and temperature level [1]. The charging and discharging process of PCMs in shell-and-tube heat exchanger type latent heat thermal energy storage unit have been an integral part of thermal energy conservation systems. As a general rule, the thermal energy systems (TES) consist of a heat storage domain with heat transfer fluid (HTF), and containment unit (shell). For the LHTES unit, thermal energy will be storage in phase-change material (PCM) as latent heat form [2]. A large array of phase-change materials and their properties were mentioned in the literature [3-8]. During the process of storage, heat transfer fluid melts the PCM under height temperature. So, the storage thermal energy in PCM will be in latent heat form. During the release process, the PCM discharges the thermal energy under a cold temperature transferred by heat transfer fluid to PCM. Numerous problems appreciated latent heat thermal energy storage system were investigated by many researchers, to develop and design an efficient and cost-effective latent heat thermal energy storage system. K. Nedjem et al [9] investigated numerically a hybrid thermal performance enhancement of shell and tube latent thermal storage. The main focus of their present work is analyzing the potential of two heat transfer augmentation methods (nano-additives and metal foam) for a shell and tube heat exchanger. Their results showed that the nano-additives and metal foam have a significant effect on the thermal performance in the shell and tube heat exchanger. In this study, the thermo-hydraulic processes in the shell-and-tube heat exchanger using phase change energy storage system involve forced convection in HTF domain, and conduction in PCM domain. Where, the present paper out to determinate the effect of the PCM containers on the thermal performance of the shell-and-tube heat exchanger during the melting and solidification process.

## IV.2 Mathematical Model

In this section, we considered the enthalpy method to study the thermal problem of PCMs. The physical problem and the boundary and initials conditions are given below in fig.1. The initial temperature is supposed to be uniform ( $T_0=293K$ ). The dimensions of the inner tube ( $D_{2-in}=29mm$  and  $D_{2-out}=30mm$ ), the dimensions of the outer tube ( $D_{1-in}=69mm$  and  $D_{1-out}=70mm$ ). The PCM store consisted of a length of 1m between the two coaxial horizontal cylinders of 19,5mm of thickness. Otherwise, the HTF is imposed to sinusoidal temperature on the external

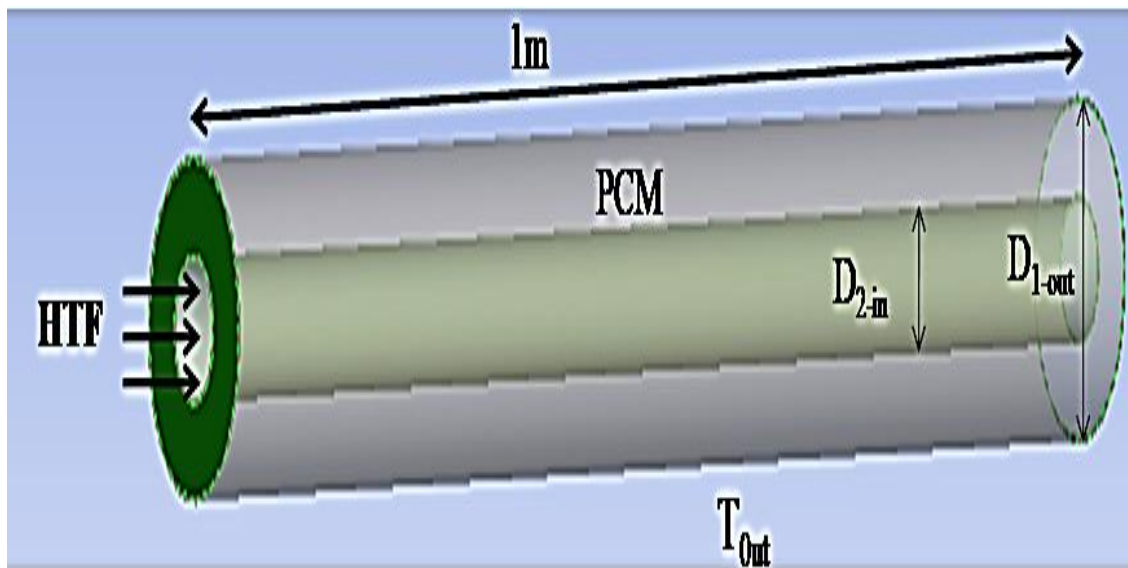
wall of exterior tube. Thus, the problem can be simplified as heat transfer by conduction through the PCMs medium.

The proposed mathematical model contains certain assumptions that are important considerations that have already been tested and don't have an influence on the creation and use of this model. It is assumed as: the PCM is homogeneous medium and isotropic, the heat transfer process in the PCM is dominated by conduction. The melting/solidification process in the PCM is assumed to be isothermal; the thermo-physical properties of PCM are different on the solid and liquid phases [10].

Given these assumptions, the enthalpy formulation for the conduction-controlled the phase change can be written as follows :

$$\frac{\partial h}{\partial t} = \text{div} \left( \frac{k}{\rho} \text{grad} t \right) - L \frac{\partial f_1}{\partial t} \quad (\text{IV.1})$$

Considering the dimensions of the geometry of the heat exchanger pipe shown in Fig. 1.



**Figure IV.1:** Geometry of the heat exchanger pipe studied.

The solution of unsteady-state heat Eq (1) to analyze heat exchanger pipe by using an implicit finite volume method, CFD software is used to calculate the temperature and heat flux in PCMs medium. To obtain converged solution, the geometry is devised in 568558 nodes, the thermophysical parameters are given in table 1.

**Table IV.1:** Thermophysical proprieties of PCM.

	PCM1(RT50)	PCM2(RT26)	PCM3(RT35)	PCM4(RT44)	PCM5(P116)
density	780	1213	815	800	818
Cp	2000	915	2000	2000	2600
Thermal conductivity	0.2	0.266	0.2	0.2	0.24
viscosity	0.03499	0.174	0.023	0.0044	0.003
Latent heat	168000	11265	157000	255000	266000
T liquidus	51	26	36	45	48

## IV.2 Numerical simulation

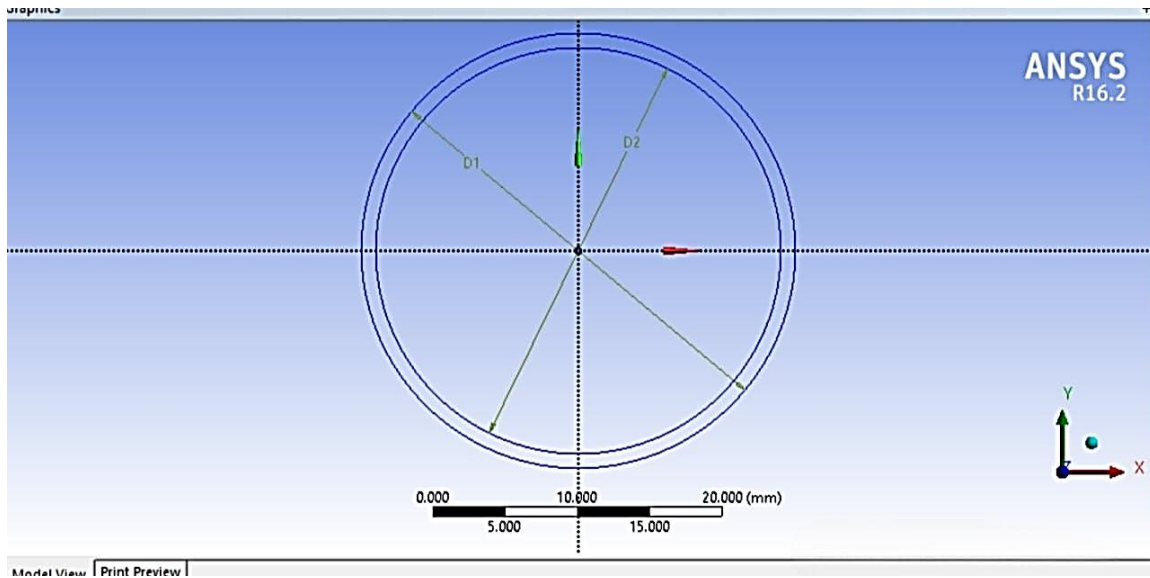
### IV.2.1 Ansys:

ANSYS Fluent is an advanced Computational Fluid Dynamics (CFD) software tool used for simulating complex fluid flow and heat transfer phenomena. In the context of thermal energy storage systems, Fluent enables numerical investigation of latent heat storage units, such as horizontal coaxial heat exchanger pipes filled with Phase Change Materials (PCMs). By employing the enthalpy-porosity method, ANSYS Fluent accurately models the melting and solidification processes of PCMs, providing valuable insights into thermal performance and heat transfer enhancement techniques. This makes it a powerful platform for analyzing and optimizing solar energy storage systems and other energy-efficient thermal applications.

### IV.2.2 Steps:

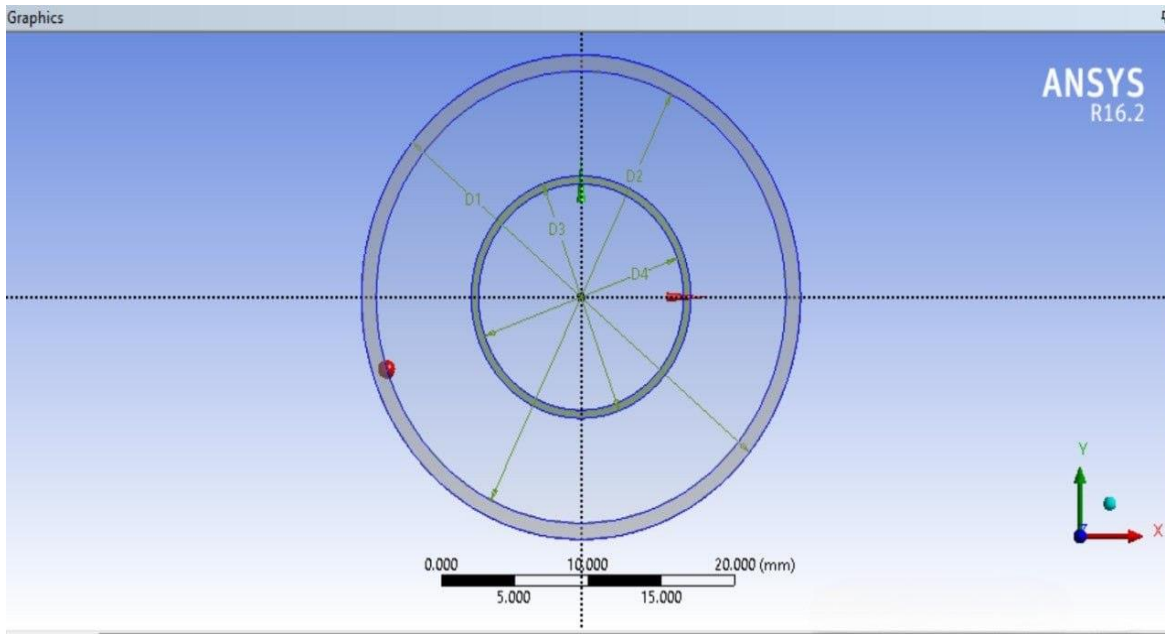
#### IV.2.2.1 Geometry

To build the geometry used in our study, the first thing we try to design with ANSYS program in cad software we change the default units setting and we start by drawing a two concentric circle and extrude to make the outer cylinder domain as the photo below.



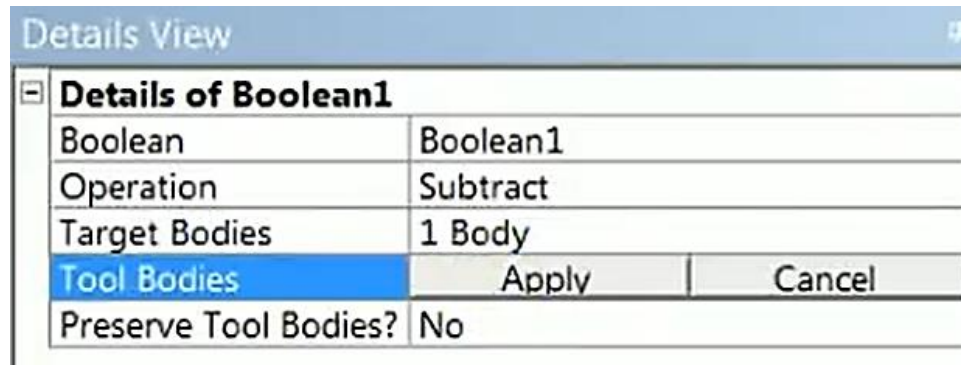
**Figure IV.2:** Concentric Circles Extruded to Cylinder.

Then we use FILL tool to create the inside fluid domain, after that we add new sketch to create a small pipe inside like the photo below.



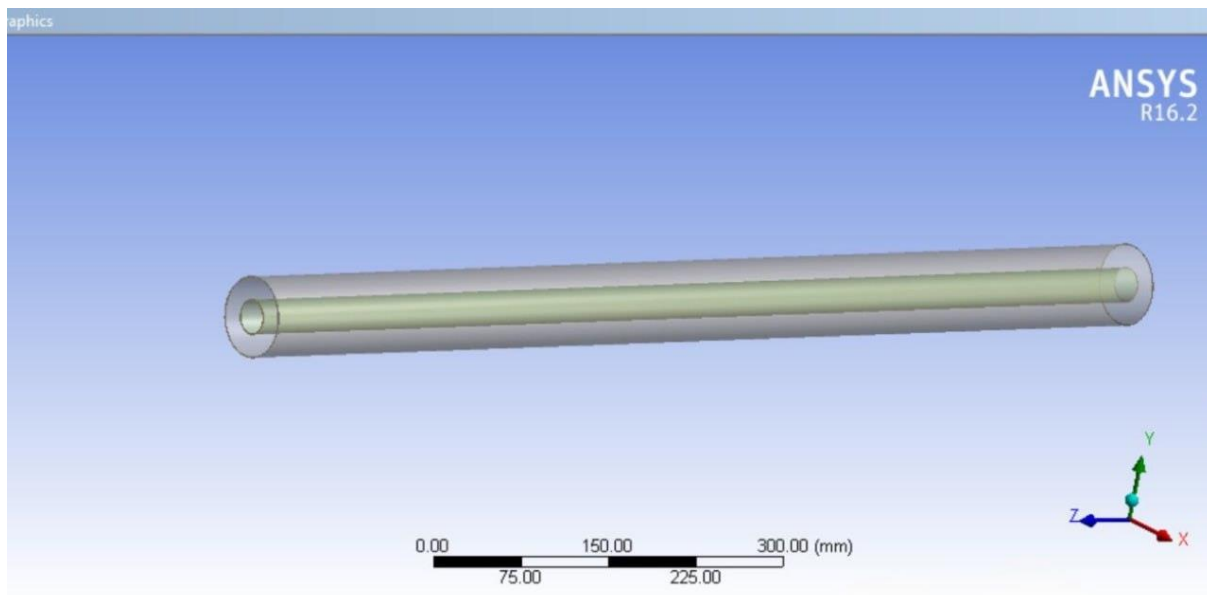
**Figure IV.3:** FILL Tool for Inner Region and Small Pipe Sketch.

In the annular region the PCM will be filled and in the inner pipe water is flowing, and we use the Boolean operation to separate the two fluids zones.



**Figure IV.4: Figure IV.9:** Activation of Toll Bodies.

And for the 4 bodies each one we rename it (inner pipe, outer pipe, inner fluid, PCM) and this is the final structure.

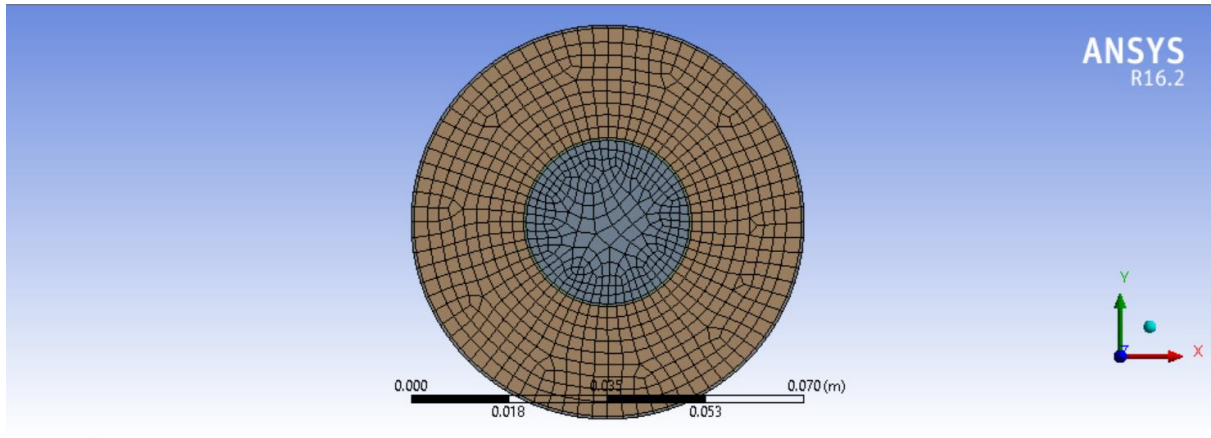


**Figure IV.5:** final structure.

#### IV.2.2.2 Mesh:

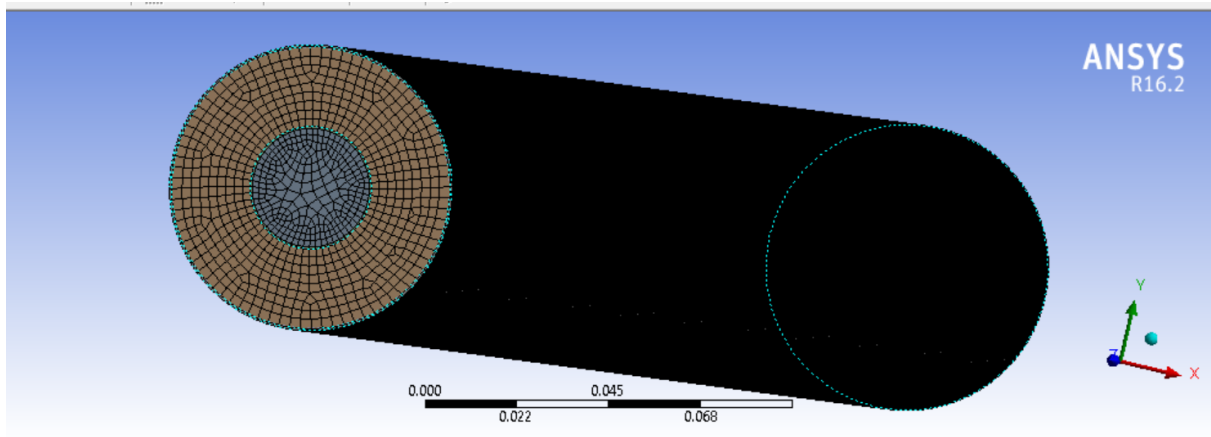
Meshing is a critical preprocessing step in numerical analysis where complex geometries are discretized into finite elements. In ANSYS R16.2, this process transforms computational domains into structured or unstructured grids, directly determining solution accuracy and convergence behavior. Proper mesh generation ensures reliable simulation results while optimizing computational efficiency.

The first thing we hide the fluid domain to select the edges of pipe by using sizing and we off the advanced function and we add in type the number of divisions and we select all the edges using CTRL and we generate the mesh, and we have as the photo below.

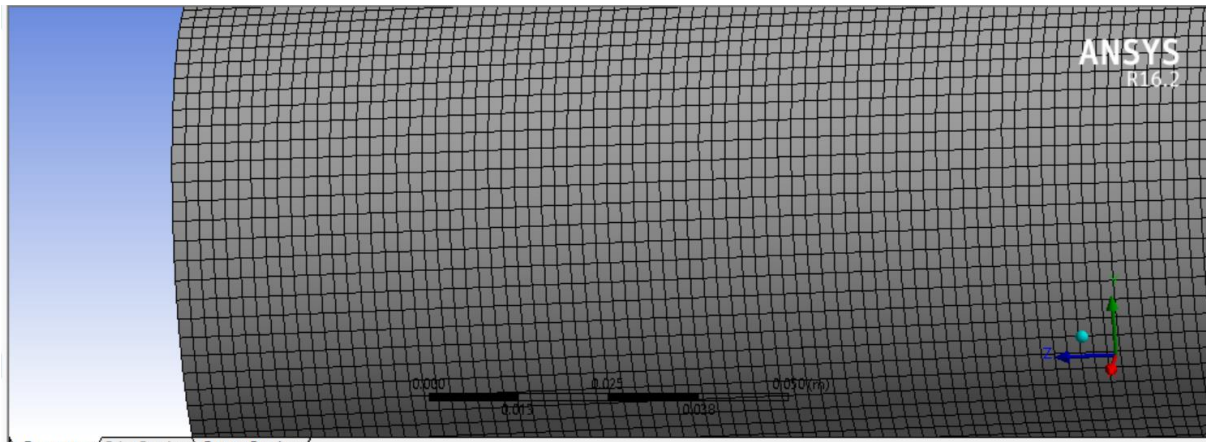


**Figure IV.6:** Mesh Setup: Edge Selection, Sizing, and Structured Discretization.

We create named selection for boundary surfaces, and this is the final structure of mesh.



(a)

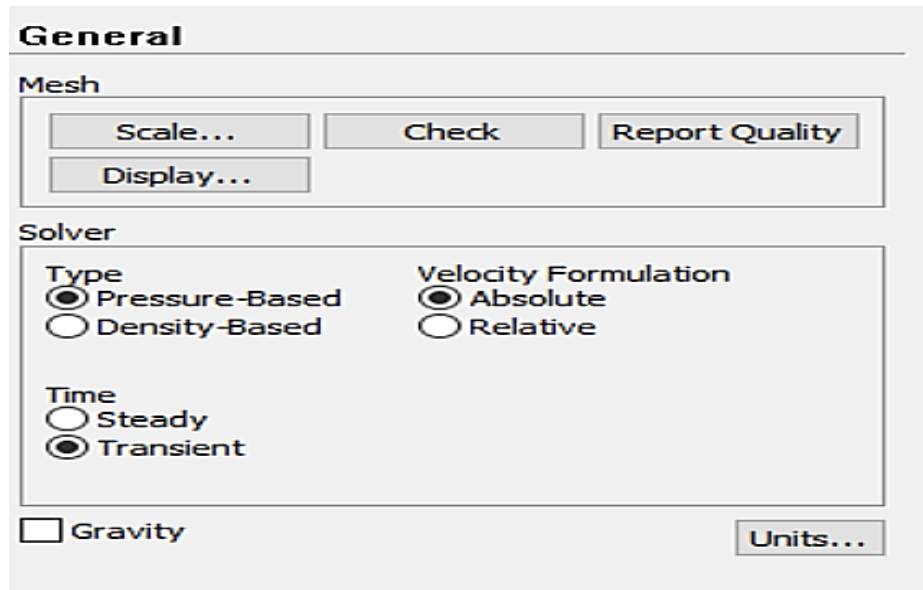


(b)

**Figure IV.7:** (a) the final refined mesh, (b) mesh of the tube part.

**IV.2.2.3 Set up:**

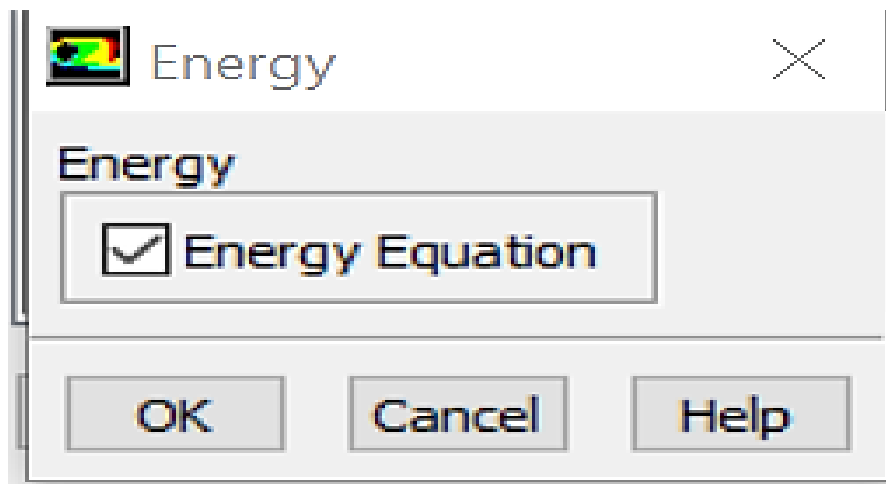
After importing the geometry and mesh files into ANSYS FLUENT, the solver type is set to "Pressure-Based "subsequently, the selection of a "transient" -state regime which means it's related to capturing the time.



**Figure IV.8:** Selection of the transient state.

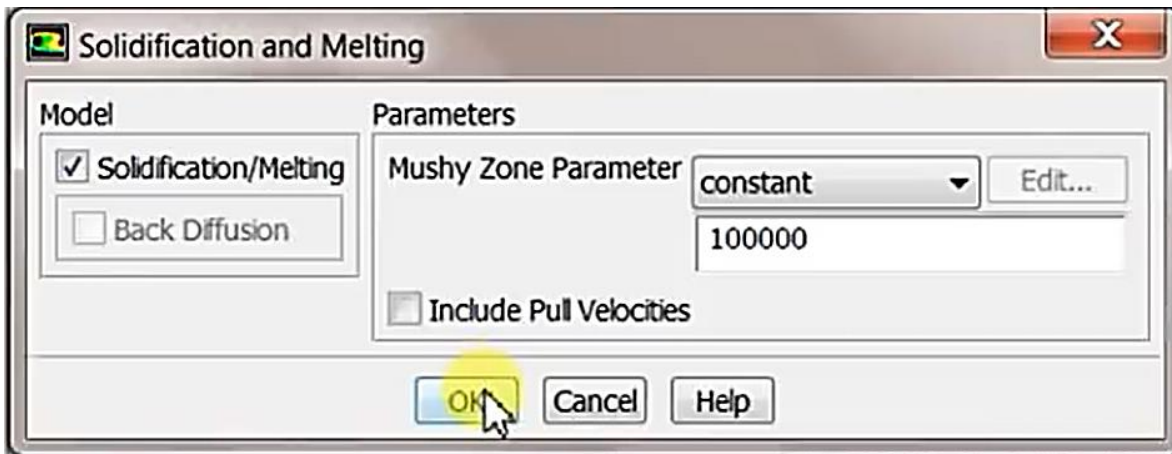
**3.1. Activation of the Energy Equation:**

Enabling the energy equation is necessary to take the thermal impact into account when addressing the problem under study.



**Figure IV.9:** Activation of the energy equation.

And at the same time, we activate the solidification and melting models.



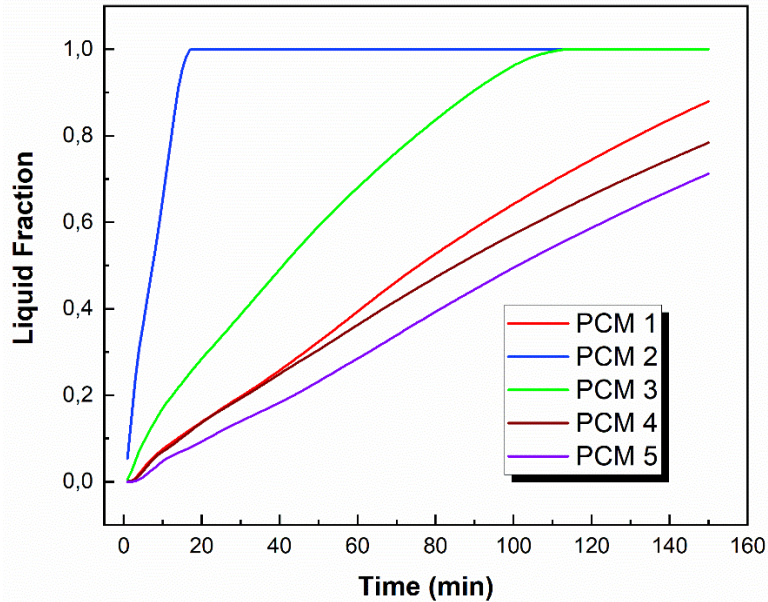
**Figure IV.10:** Activation of solidification and melting.

Then we add our materials for PCM, and we create the PCM property Launching the calculation after all the steps are completed and we have those results.

### IV.3 Results and discussions

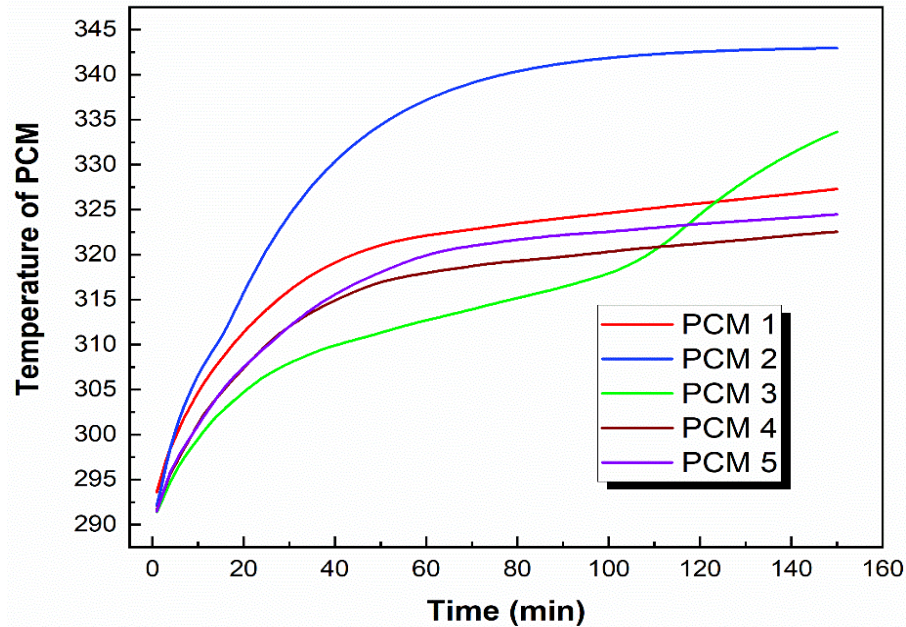
**Case 1:**  $U_{in}=0.015$  m/s; $T_{in}= 343$  K.

Figure IV.11 shows the variation of the liquid fraction of five different phase change materials (PCM 1 to PCM 5) over time. This data is crucial for assessing the thermal performance of energy storage or thermal management, as it reveals how quickly and completely each material transitions from solid to liquid under specific conditions. By comparing the liquid Fraction trends across the five samples, researchers can evaluate differences in melting rates, which may stem from variations in composition (e.g., additives, purity), thermal conductivity, or latent heat capacity. The absence of numerical values or graphical data limits precise analysis, but the structure suggests an experimental or simulation-based study where melting behavior was monitored at intervals. For deeper insights, plotting liquid fraction against time could highlight which PCM achieves faster or more uniform melting, informing material selection of targeted applications. Additional context, such as temperature conditions or PCM formulations would further clarify the observed trends.



**Figure IV.11:** variation of the liquid fraction of five different phase change materials.

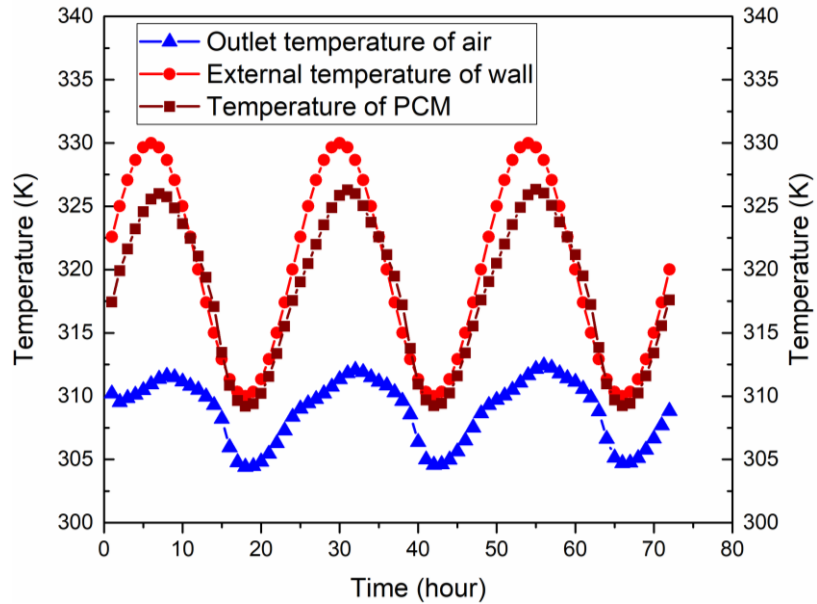
Figure IV.12 depicts the average temperature evolution of five phase change materials (PCM 1–5) over time, revealing distinct thermal characteristics critical for energy storage applications. Each PCMs curve exhibits an initial sensible heating phase with a steady temperature rise. The slopes preceding and following the temperature range reflect thermal conductivity differences, where steeper heating rates imply faster heat transfer, potentially due to enhanced thermal diffusivity or the presence of conductive additives. Notably, PCMs with higher onset temperatures for melting (visible as temperature range at elevated temperatures) may be better suited for high-temperature applications, while those melting at lower temperatures could optimize systems requiring moderate thermal regulation. Discrepancies in the equilibrium temperatures post-phase change may arise from variations in material composition, encapsulation, or experimental conditions.



**Fig IV.11:** the average temperature of PCM.

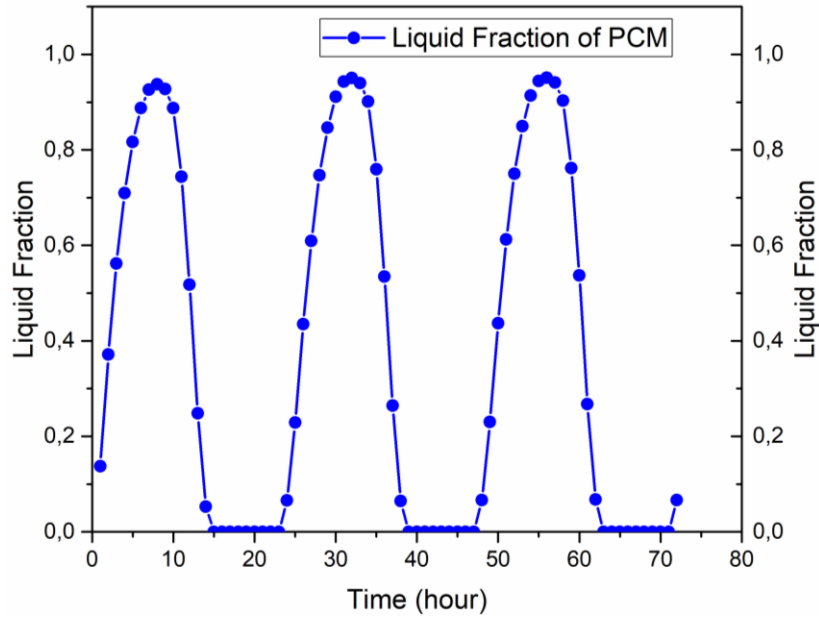
**Case 2:**  $U_{in}$ : 0.015m/s;  $T_{in}$ = 293 K;  $T_w = 320 + 10\sin(\omega t)$ .

Figure IV.13 shows the average temperature of PCM, external wall temperature and outer temperature of air during the solidification and melting process in the heat exchanger pipe. The solid PCM absorbs thermal energy via the external wall, and transfers into HTF. The present results compared to external temperature show a fluctuation of outlet air temperature around  $\Delta T=8^\circ\text{C}$ . It's possible to identify the effect of thermal energy storage on the shell-and- tube heat exchanger, the melting and solidification process of PCM is very important to maintain the outlet air temperature between 304 K and 312 K.



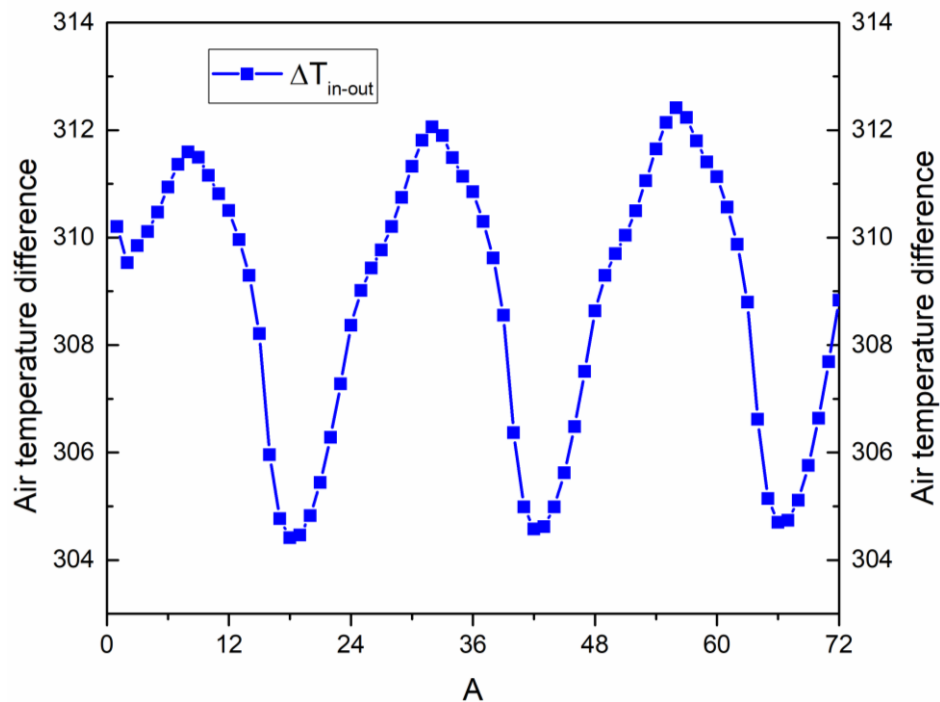
**Fig IV.13:** Transient variations of temperature profiles in the heat exchanger pipe.

Fig. IV.14 shows the transient variation of liquid fraction of the PCM during the melting and solidification process under sinusoidal outdoor temperature variation. So, the liquid fraction varied between  $[0,1]$  from a complete solid phase to complete liquid phase. As observed, an incomplete liquid phase was shown in this numerical result. As was discussed in the previous paragraph, the liquid fraction of PCM container is one of the essential parameters to optimize the dimensions of thermal storage systems. So, the melting time of PCM is the most important parameter to identify the efficiency of our thermal storage system.



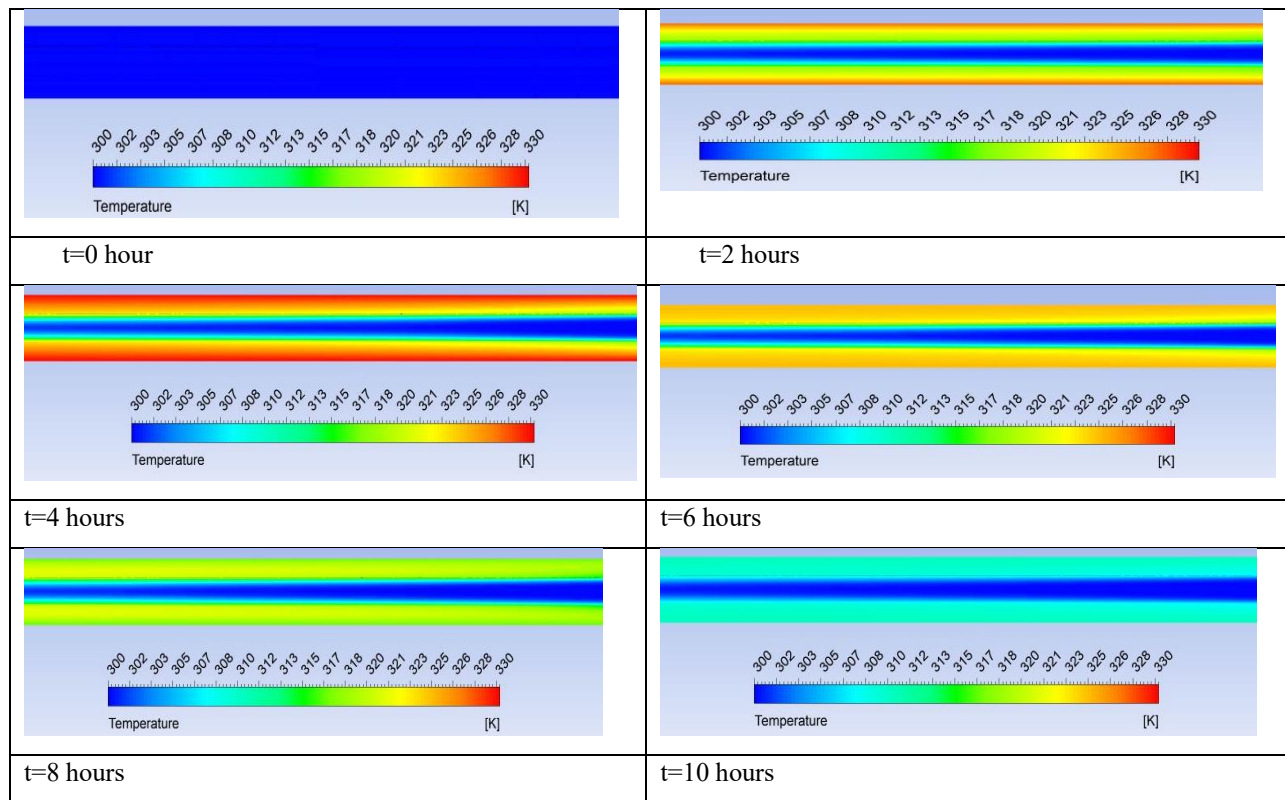
**Fig IV.14:** Transient variations of liquid fraction profile of PCM.

In the same manner, figure IV.15. Presents the air temperature difference between inlet and outlet HTF, the difference in air temperature during the time simulation indicates that this fluctuation results in imposed outside temperature near the HTF tube. However, this difference in air temperature is interesting to note that the shell-and-tube heat exchanger using PCM is preferable and applicable in many industrial arrays.



**Fig. IV.15:** Air temperature difference between inlet and outlet HTF.

The temperature contours along with the heat exchanger after pipe 2, 4, 6, 8 and 10 hours are given in figure IV.16. It is observed that the PCM container transfer heat flux via the imposed external temperature to HTF, the results show significant change between the two domains (PCM and HTF) during the charging/discharging process.

**Fig IV.16.:** Temperature Contours of heat exchanger pipe during melting and solidification process.

A numerical simulation for shell-and-tube heat exchanger using PCM has been presented in this paper. The melting and solidification process of PCM is more effective, because its influence on the outlet air temperature is clearly observed in present work. Therefore,

The numerical results showed that the RT50 can increase the imposed temperature with  $\Delta T_{\max}=19^{\circ}\text{C}$  and  $\Delta T_{\min}=6^{\circ}\text{C}$ , and the outer air temperature fluctuated between  $38^{\circ}\text{C}$  and  $31^{\circ}\text{C}$ . difference was observed. Finally, the application of PCM containers in shell-and-tube heat exchanger should be the best way to maintain the HTF temperature in the range melting temperature and decrease the energy consumption.

#### IV.4. Conclusion

This study numerically analyzed a shell-and-tube latent heat thermal energy storage system using various phase change materials (PCMs). The results showed that PCM selection, particularly RT50, significantly influences heat transfer performance and temperature stability. The PCM effectively reduced temperature fluctuations in the heat transfer fluid, confirming its role in thermal regulation. The system's performance under changing external temperatures highlights its potential for energy-efficient applications in HVAC and industrial heat recovery. Future work should focus on experimental validation and enhanced heat transfer methods to improve system efficiency.

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# **General Conclusion**

## **General Conclusion**

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Phase Change Materials (PCMs) represent one of the promising solutions to enhance the efficiency of thermal energy storage in various applications. In this research, we analyzed the performance of a thermal energy storage system using PCMs through a study of several numerical scenarios, focusing on shell-and-tube heat exchange systems.

The results demonstrated that the selection of appropriate materials, such as RT50, significantly influences thermal performance and temperature stability within the system. The integration of PCMs in thermal energy storage systems can reduce temperature fluctuations in the heat transfer fluid, contributing to the overall improvement of system efficiency.

The research also addressed the complex thermal mechanisms occurring during melting and solidification processes, emphasizing the importance of understanding the dynamics of these processes to achieve optimal energy performance. Advanced numerical methods, such as the effective capacity method and the enthalpy method, were employed, facilitating the development of accurate models to predict material behavior under various conditions.

In conclusion, this research represents a significant step toward improving thermal energy storage technologies using Phase Change Materials. Future studies should focus on experimental validation of the presented numerical results, as well as exploring new methods to enhance heat transfer and increase system efficiency. Advancements in this field can contribute to achieving sustainability goals and reducing reliance on traditional energy sources, thereby supporting global environmental.



