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### Investigation on a Storage Tank for a Flat-Plate Solar Collector

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## Abbreviation

|        |                            |
|--------|----------------------------|
| DHW    | Domestic Hot Water         |
| FPC    | Flat-Plate Collector       |
| FPSC   | Flat-Plate Solar Collector |
| HTF    | Heat Transfer Fluid        |
| MATLAB | Matrix Laboratory          |
| PCM    | Phase Change Material      |
| SST    | Stratified Storage Tank    |
| SWH    | Solar Water Heating        |
| TES    | Thermal Energy Storage     |

# Nomenclature

| Symbol                      | Description                                      | Unit                                |
|-----------------------------|--------------------------------------------------|-------------------------------------|
| A                           | Heat Transfer surface area                       | m <sup>2</sup>                      |
| A <sub>i</sub>              | Heat transfer surface area of layer i            | m <sup>2</sup>                      |
| C <sub>p</sub>              | Specific heat capacity of the working fluid      | J·kg <sup>-1</sup> ·K <sup>-1</sup> |
| F <sub>i</sub> <sup>c</sup> | Collector control function for layer i           | —                                   |
| F <sub>i</sub> <sup>L</sup> | Load control function for layer i                | —                                   |
| H                           | Tank height                                      | m                                   |
| m                           | Mass                                             | kg                                  |
| m <sub>i</sub>              | Mass of fluid contained in layer i               | kg                                  |
| $\dot{m}$                   | Mass flow rate                                   | kg·s <sup>-1</sup>                  |
| $\dot{m}_c$                 | Collector-loop mass flow rate                    | kg·s <sup>-1</sup>                  |
| $\dot{m}_L$                 | Load-loop mass flow rate                         | kg·s <sup>-1</sup>                  |
| $\dot{m}_{m,i}$             | Net inter-layer mixing mass flow rate at layer i | kg·s <sup>-1</sup>                  |
| N                           | Number of tank layers or nodes                   | —                                   |
| P                           | Thermal power                                    | W                                   |
| Q                           | Quantity of heat or thermal energy               | J                                   |
| $\dot{Q}$                   | Heat Transfer rate                               | W                                   |
| $\dot{Q}_{ch}$              | Useful charging power from collector to tank     | W                                   |
| $\dot{Q}_{dis}$             | Useful discharging power from tank to load       | W                                   |
| $\dot{Q}_{loss}$            | Heat loss rate to the ambient environment        | W                                   |
| r                           | Tank radius                                      | m                                   |
| t                           | Time                                             | s                                   |
| T                           | Temperature                                      | K or °C                             |
| T <sub>i</sub>              | Temperature of layer i                           | K or °C                             |
| T <sub>amb</sub>            | Ambient temperature                              | K or °C                             |
| T <sub>c, out</sub>         | Collector outlet temperature                     | K or °C                             |
| T <sub>L</sub>              | Load return temperature                          | K or °C                             |

|            |                                               |                                                    |
|------------|-----------------------------------------------|----------------------------------------------------|
| U          | Overall Heat Transfer coefficient             | $\text{W} \cdot \text{m}^{-2} \cdot \text{K}^{-1}$ |
| $UA_i$     | Heat loss coefficient-area product of layer i | $\text{W} \cdot \text{K}^{-1}$                     |
| V          | Volume                                        | $\text{m}^3$                                       |
| z          | Vertical position or height coordinate        | m                                                  |
| $\Delta t$ | Numerical time step                           | s                                                  |
| $\Delta T$ | Temperature difference                        | K or $^{\circ}\text{C}$                            |

## Indices

| Subscript / Index | Meaning                                   |
|-------------------|-------------------------------------------|
| Amb               | Ambient environment                       |
| C                 | Collector loop                            |
| Ch                | Charging process                          |
| Des               | Destocked or discharged energy            |
| Dis               | Discharging process                       |
| F                 | Fluid                                     |
| I                 | Index of a tank layer or node             |
| J                 | Secondary spatial index                   |
| L                 | Load loop                                 |
| Loss              | Thermal losses                            |
| M                 | Mixing flow                               |
| mod stk           | Storage module                            |
| N                 | Last tank layer or total number of layers |
| Out               | Outlet                                    |
| R                 | Return flow                               |

## ملخص

يستكشف هذا البحث الخزان الطبقي إلى جانب المجمع الشمسي ذو اللوحة المسطحة. يتم تقييم الأداء الحراري لخزانات التخزين الحراري الشمسي باستخدام نموذج حراري متعدد الأبعاد أحادي البعد، تمت برمجة النموذج الرياضي في ماتيلا باستخدام تقنيات تقدير الوقت الصريحة من أجل تحليل التغيرات في درجات الحرارة، والتقسيم الطبقي الحراري، وسعة الشحن المفيدة، وملف التفريغ، والتوازن الحراري للدورات المختلفة (الشحن، والوقوف، والتفريغ). تكشف النتائج أن بعض العوامل التشغيلية مثل معدل تدفق الشحن، ومعدل تدفق التفريغ، وكتلة الخزان، وعامل فقدان الحرارة لها تأثيرات كبيرة على أداء نظام التخزين. أظهرت نتائج المحاكاة أن الخزان الطبقي حافظ على تدرج واضح في درجة الحرارة، حيث خزنت الطبقات العليا الحرارة بشكل أكثر فعالية أثناء الشحن وظلت أكثر سخونة أثناء التفريغ. تؤكد هذه النتائج أن معدلات التدفق المناسبة وكتلة الخزان المناسبة وتقليل فقد الحرارة ضرورية لتحسين مدة التخزين والأداء الحراري العام.

## Abstract

This research explores the stratified tank coupled with the flat-plate solar collector. The thermal performances of the solar thermal storage tanks, are evaluated using a thermal multi-node one-dimensional model. The mathematical model is programmed in MATLAB using explicit time-discretization techniques in order to analyze the temperature variations, thermal stratification, useful charge capacity, discharge profile, and thermal balance for the different cycles (charge, stand by, and discharge). The findings reveal that some operational factors like charging flow rate, discharging flow rate, mass of the tank, and heat loss factor have great impacts on the performance of the storage system. The simulation results showed that the stratified tank maintained a clear temperature gradient, where the upper layers stored heat more effectively during charging and remained hotter during discharging. These findings confirm that suitable flow rates, proper tank mass, and reduced heat losses are essential to improve storage duration and overall thermal performance.

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## **Générale introduction**

In recent years, the global shift towards clean and renewable energy has become increasingly urgent, driven by the need to reduce dependence on fossil fuels and mitigate their environmental consequences. Among the available renewable options, solar energy stands out as one of the most abundant and accessible alternatives, playing a vital role in building a more sustainable future.

Flat-plate solar collectors represent one of the most practical and widely adopted means of harnessing solar thermal energy. They capture heat from the sun and transfer it to a working fluid, typically water, serving everyday needs such as domestic hot water supply, space heating, and low-temperature industrial processes.

However, solar energy availability is disrupted by nighttime, changing weather, and seasonal shifts, creating a mismatch between energy production and demand. To bridge this gap, a thermal storage tank is essential. Acting as a thermal reservoir, it stores collected heat during sunny periods for use when solar irradiance is unavailable.

The performance of the storage system depends largely on thermal stratification — the natural separation of water layers by temperature and density. Maintaining this stratification ensures that the hottest water remains at the top for immediate use, while cooler water at the bottom is returned to the collector for reheating, maximizing overall system efficiency.

With these principles in mind, this study investigates the thermal behavior of a stratified storage tank coupled to a flat-plate solar collector across its three operating phases: charging, discharging, and standby. A five-node modeling approach is adopted to track temperature evolution within each layer, with the aim of providing practical insights for improving storage tank design and solar heating system performance.

# **1. Chapter I : Introduction and Literature Review**

## 1.1 Introduction :

A storage tank for a flat-plate solar collector is a thermal energy storage unit used in solar thermal systems to store hot water or a heat transfer fluid heated by a flat-plate solar collector. Its main function is to preserve the collected solar energy for later use when solar radiation is not available, such as during nighttime or cloudy periods. The storage tank ensures a continuous thermal energy supply by reducing the mismatch between energy production and demand. In many systems, it is designed to support thermal stratification, where hotter water remains at the top and colder water stays at the bottom, improving overall system efficiency by maintaining lower inlet temperatures for the collector. Overall, this component plays a critical role in enhancing the performance, reliability, and energy efficiency of flat-plate solar collector systems.

This technological development is critical because global energy demand has been increasing steadily due to population growth, industrial expansion, and improved living standards. However, the extensive use of fossil fuels has led to serious environmental challenges, including greenhouse gas emissions, climate change, and resource depletion [3], [4]. Consequently, renewable energy technologies have become essential for achieving sustainable development. Among these sources, solar energy is one of the most promising due to its abundance, sustainability, and environmental compatibility [2]. Solar energy systems can generate electricity or produce thermal energy without harmful emissions, and solar thermal systems, in particular, are widely used for domestic and industrial water heating applications.

The “Flat-Plate Solar Collector” (**FPC**), is one of the most commonly implemented solar thermal technologies. It converts incident solar radiation into thermal energy and transfers this heat to water or to a heat transfer fluid, typically a water–glycol mixture [1]. Due to its simple construction, reliability, and relatively low cost, the flat-plate collector is extensively used in residential and small industrial applications. However, solar radiation is inherently intermittent; it varies throughout the day and is unavailable during nighttime or cloudy periods. Therefore, integrating a thermal energy storage system is essential to store excess heat during peak solar radiation hours, supply hot water during periods without sunlight, improve overall system efficiency, and maintain temperature stability.

The central component of this storage system is the hot water storage tank, which significantly influences the overall thermal efficiency, heat loss rate, thermal stratification behavior, and duration of energy availability. Understanding the internal heat transfer mechanisms within the storage tank—including conduction, natural convection, and thermal stratification—is crucial for optimizing system performance. Proper tank design can enhance the solar fraction, reduce auxiliary energy consumption, and improve long-term system reliability [1], [2].

Consequently, the investigation of storage tanks coupled with flat-plate solar collectors is highly motivated by several technical, economic, and environmental considerations. Poorly designed storage tanks lead to excessive thermal losses and internal mixing, which reduce the temperature of the delivered hot water. Improving tank design directly enhances overall solar heating system efficiency. Crucially, thermal stratification—where hot water remains at the top and cold water at the bottom—serves as a key performance indicator. Good stratification allows the collector to operate at lower inlet temperatures, thereby increasing collector efficiency, meaning tank geometry and inlet/outlet configurations play a decisive role in maintaining this behavior [2], [5]. Furthermore, heat losses through tank walls significantly affect stored energy capacity, making the investigation of insulation materials and optimal insulation thickness vital for improving energy retention. Ultimately, optimized storage systems reduce auxiliary heating demand, decrease operating costs, and improve the economic feasibility of solar heating systems. By strengthening the performance of these storage configurations, solar thermal systems can better contribute to reducing CO<sub>2</sub> emissions and decreasing dependence on non-renewable energy sources, reinforcing the role of solar heating in achieving global sustainability goals [3], [4].

## **1.2 Literature Review**

### **1.2.1 Review of Recent Studies on Solar Thermal Storage Systems**

In recent years, significant progress has been made in the design of thermal storage tanks associated with flat-plate solar collectors, aiming to increase overall system efficiency and reduce operational costs. Accordingly, this section reviews and analyzes five recent studies (conducted between 2025 and 2026) representing the latest scientific research in this field. These studies cover a variety of vital topics, ranging from the use of Phase Change Materials and thermal fins, to the impact of dust accumulation on tank size, to the comparison of alternative storage media

such as salt and sand, in addition to hybrid systems that integrate electricity generation with thermal storage.

### **1.2.2 Finned PCM Storage Tank for Nighttime Heat Supply**

This numerical study investigates a finned storage tank integrating Phase Change Materials (PCMs) to address solar energy's intermittency. The researchers developed a 2D transient model of a flat-plate solar collector coupled with a PCM storage tank, analyzing the effect of extended surfaces (fins) on thermal performance.

The use of PCMs allows energy received during daylight hours to be stored as latent heat and released at night, extending the system's operational period. The incorporation of fins significantly enhances both energy storage and release rates by mitigating PCMs' low thermal conductivity. Increasing flow velocity also improves the freezing (discharging) rate, and fins further accelerate this process compared to finless configurations. The fins also promote more uniform thermal flow distribution within the air channel. [13]

### **1.2.3 Dust Accumulation and Optimal Tank Sizing**

This techno-economic study quantifies how dust accumulation on flat-plate collectors affects required storage tank capacity and system economics for residential applications in arid climates (Dhahran, Saudi Arabia). The research used MATLAB simulations with hourly-based optimization incorporating experimental dust transmittance data.

For a clean collector surface, optimal component sizes were a 1 m<sup>3</sup> storage tank and 9 m<sup>2</sup> collector area. Under dust accumulation densities of 2.1 mg/m<sup>2</sup>, the required tank capacity increases to 1.4 m<sup>3</sup> and collector area to 19 m<sup>2</sup> to meet identical hot water demand. The Cost of Energy (COE) increases from 0.128/kWh (clean) to 0.219/kWh—a 71% increase under heavy dust conditions. This demonstrates that dust accumulation directly impacts required storage sizing and overall system cost-effectiveness. [14]

### **1.2.4 Alternative Storage Media: Salt, Sand, and Water**

This experimental study compared the sensible heat storage performance of three different materials (salt, sand, and water) in a flat-plate solar collector system under controlled indoor conditions, with a heat exchanger facilitating thermal exchange in a storage tank containing mixed media.

Water demonstrated superior specific heat capacity at  $4.1969 \text{ kJ/kg}\cdot\text{K}$ , making it most effective for heat retention. However, salt exhibited the highest thermal storage efficiency at 76.67%, outperforming both sand and water under the tested conditions. Sand showed the lowest specific heat capacity ( $0.7440 \text{ kJ/kg}\cdot\text{K}$ ) but remains the most cost-effective option. The study identified challenges including water evaporation, salt crystallization risks, and sand's insulating properties, suggesting hybrid approaches may be optimal. [15]

### 1.2.5 PCM-TEG Hybrid Storage Tank System

This study presents a novel hybrid system integrating a rectangular Fresnel lens concentrator with a 200 L PCM-assisted storage tank and thermoelectric generator (TEG) modules mounted on the tank's external surface. Combined experimental and numerical investigations were conducted to evaluate simultaneous heat and electricity generation.

The system achieved a maximum fluid temperature of  $200^{\circ}\text{C}$  and total thermal efficiency of approximately 97%—exceptionally high for solar thermal systems. The PCM contributes daily energy storage capacities ranging from 2 to  $7.2 \text{ kWh}\cdot\text{m}^{-2}$  depending on climatic conditions, demonstrating strong seasonal adaptability. TEG modules achieved conversion efficiencies up to 4.3%. Economic analysis showed a 25.6% return on investment with a 3.4-year payback period, confirming cost-effectiveness for residential and industrial applications. [16]

### 1.2.6 Seasonal Stratification in Indirect SWH Systems

This numerical investigation examined an indirect solar water heating system with a stratified storage tank (using an immersed coil heat exchanger) under the continental climate conditions of Central Asia. Detailed Python models were developed and validated against experimental data and TRNSYS simulations for five representative cities.

The validated framework accurately captures thermal stratification, thermocline formation, and pump control behavior. Summer performance yields tank temperatures above  $60^{\circ}\text{C}$ , enabling domestic hot water supply without auxiliary heating. Winter and autumn seasons require supplementary electric heating due to lower solar availability. Thermal stratification improved system performance by maintaining temperature layers within the tank, reducing mixing losses compared to well-mixed tank configurations. [17]

### 1.3 Conclusion :

This chapter introduced the critical role of thermal energy storage tanks in flat-plate solar collector systems, highlighting their function in reducing the mismatch between solar energy availability and thermal demand. A comprehensive review of recent studies (2025–2026) was conducted, covering key topics such as the integration of Phase Change Materials (PCMs) with finned configurations, alternative storage media (salt, sand, and water), hybrid systems combining PCM storage with thermoelectric generators (TEGs), and seasonal stratification behavior in indirect solar water heating systems. The findings confirm that several factors significantly influence overall system performance, including storage tank geometry, thermal stratification maintenance, insulation thickness, inlet/outlet configurations, and environmental conditions such as dust accumulation. Specifically, dust accumulation in arid climates was shown to increase required tank capacity by up to 40% and energy costs by 71%. Meanwhile, PCMs with fins extended nighttime heat supply, and hybrid TEG systems achieved nearly 97% thermal efficiency with a payback period of only 3.4 years. Therefore, optimizing storage tank design is essential for enhancing collector efficiency, reducing auxiliary energy consumption, lowering operating costs, and improving the economic and environmental viability of solar thermal systems.

## **2 Chapter II**

### **System Description and Working Principles**

## 2.1 Introduction :

This chapter provides a clear explanation of how solar thermal storage systems work and describes their main components. First, we compare the different types of storage tanks, such as direct (open-loop), indirect (closed-loop), thermosiphon systems, as well as phase change material (PCM) tanks and large-scale seasonal thermal energy storage (STES). Following this comparison, we focus on the **Stratified Storage Tank (SST)** connected to a **Flat-Plate Solar Collector (FPSC)**, which is the specific system chosen for this study. We explain in detail the tank geometry, the solar collector design, and the fluid handling components, alongside the three operating modes of the system: charging, discharging, and standby

## 2.2 different types and designs for solar thermal storage tank

### 2.2.1 Direct (Open-Loop) Storage Tank System

The direct or open-loop storage tank system is considered one of the simplest solar thermal storage configurations. In this design, water is heated directly inside the solar collector without the use of a heat exchanger. The heated water then flows to the storage tank either through a pump or by natural circulation. This system is characterized by its simple construction, low installation cost, and high thermal efficiency because heat is transferred directly to the water. However, direct systems are highly sensitive to freezing conditions and may experience scaling and corrosion due to mineral deposits in the water. For this reason, they are mainly used in warm climates and small residential solar water heating applications such as figure II.1

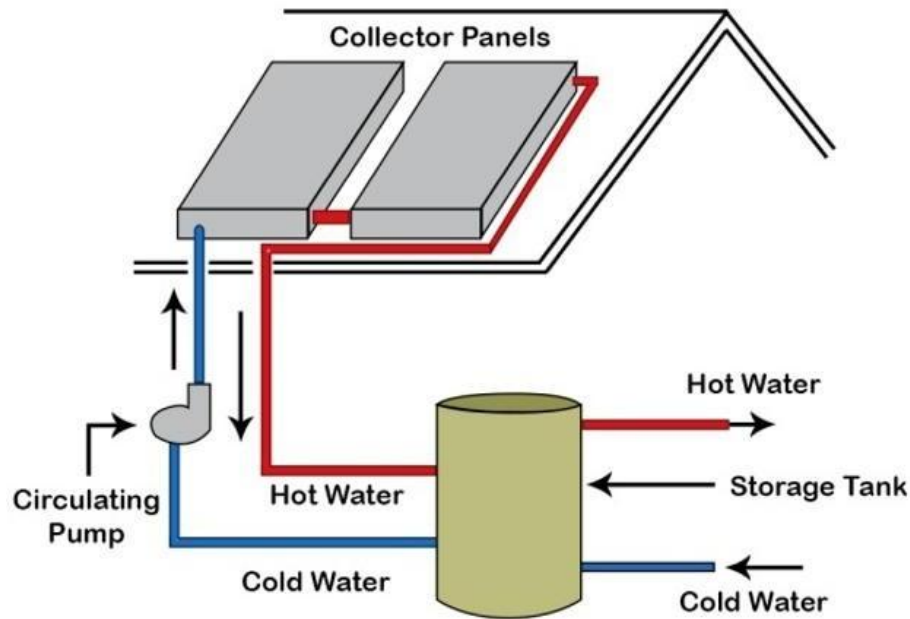


Figure II.1: Direct (Open-Loop) Storage Tank System

### 2.2.2 Indirect (Closed-Loop) Storage Tank System

The indirect or closed-loop storage tank system uses a separate heat transfer fluid as shown in figure II.2, commonly a mixture of water and glycol, circulating through the solar collector. The absorbed heat is transferred to domestic water through a heat exchanger located inside or outside the storage tank. This configuration provides effective freeze protection and minimizes scaling inside the collector, which improves system durability and operational reliability. Nevertheless, indirect systems are generally more expensive and involve additional maintenance because of the extra components and heat exchanger losses. These systems are widely applied in cold climates and modern high-efficiency solar heating installations.

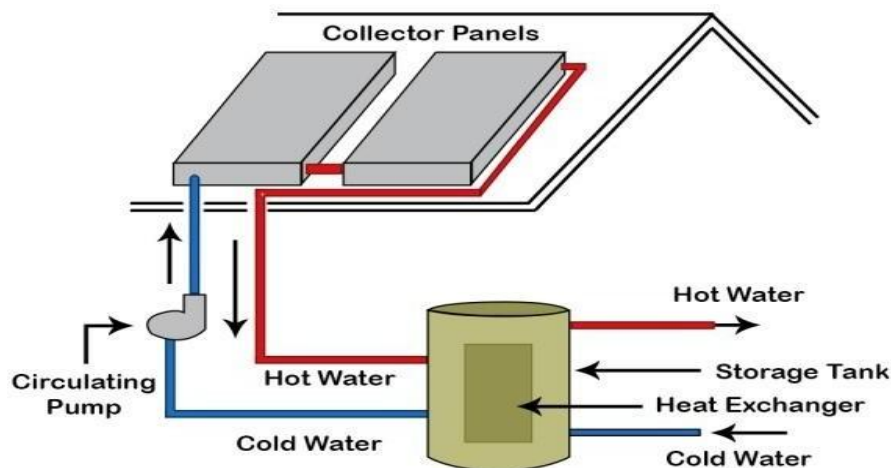


Figure II.2: Indirect (Closed-Loop) Storage Tank System

### 2.2.3 Thermosiphon Storage Tank System

The thermosiphon system operates according to the principle of natural circulation and does not require electrical pumps. In this arrangement, the storage tank is positioned above the solar collector so that hot water naturally rises into the tank while cooler water descends toward the collector exactly as shown in figure II.3, Thermosiphon systems are valued for their simple design, low operating cost, and independence from electricity, making them suitable for rural and remote areas. However, the system requires precise tank positioning and offers limited control over fluid circulation and flow regulation.

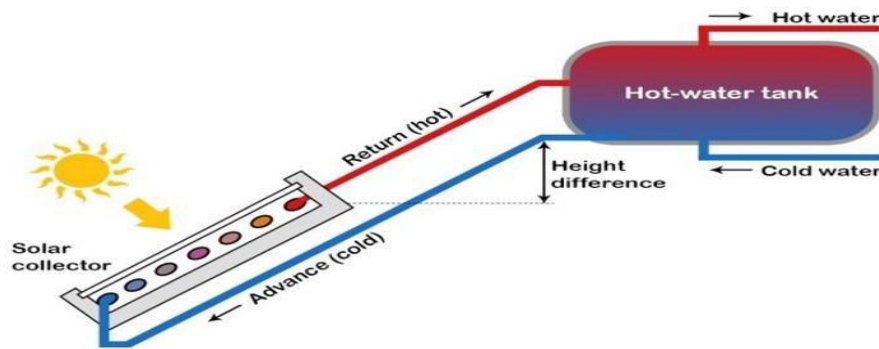


Figure II.3: Thermosiphon Storage Tank System [28]

### 2.2.4 Stratified Storage Tank

The stratified storage tank is specifically designed to preserve thermal layers inside the tank as represented in figure II.4. In this system, hot water from a flat-plate solar collector (FPSC) remains in the upper section while colder water stays at the bottom due to density differences. Vertical cylindrical tanks equipped with inlet diffusers are commonly used to reduce internal mixing. Thermal stratification enhances the efficiency of solar collectors and improves overall system performance by maintaining stable temperature layers. Despite these benefits, stratified tanks involve more complex designs and are sensitive to turbulence and internal mixing effects. They are commonly employed in medium- and large-scale solar thermal systems and research applications. [1], [11], [12], [17].

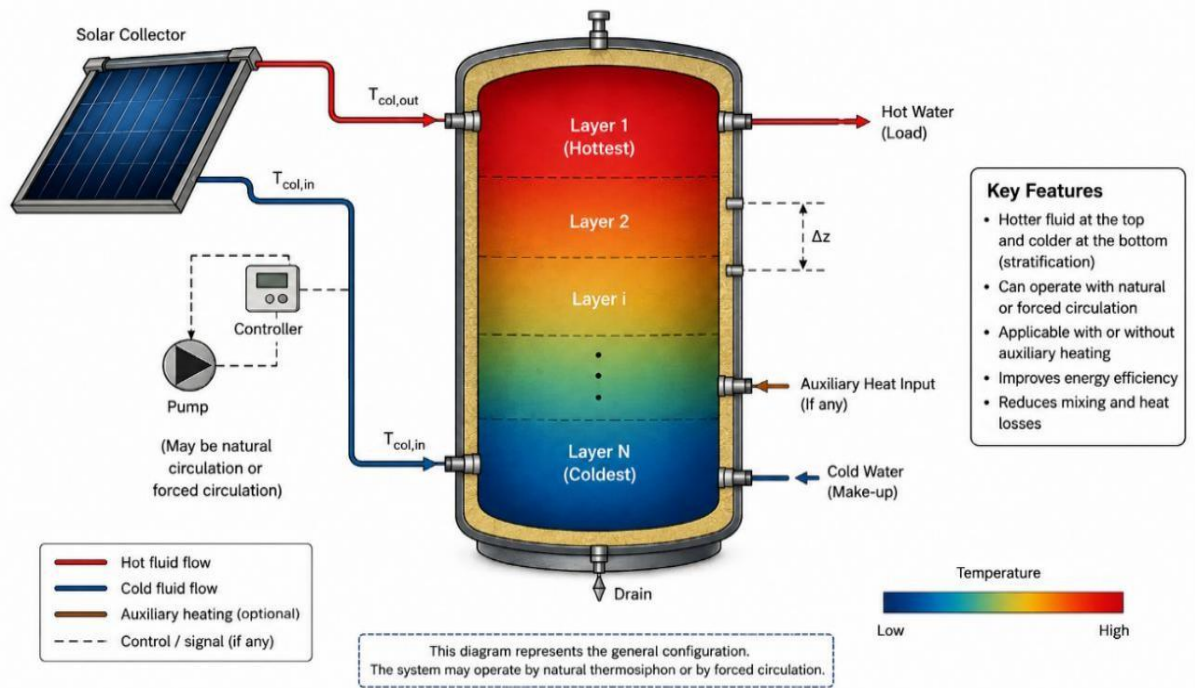


Figure II.4: Stratified Storage Tank

### 2.2.5 Phase Change Material (PCM) Storage Tank

The phase change material (PCM) storage tank integrates special materials such as paraffin wax within or around the storage tank. Thermal energy is stored in the form of latent heat during the melting process and released during solidification as illustrated in figure II.5. PCM technology allows significantly higher energy storage density and reduces the required tank volume. Despite these advantages, PCM systems remain expensive and technically complex, while some materials suffer from limited thermal conductivity. Therefore, they are mainly used in advanced research and high-performance thermal energy storage application [2],[23]

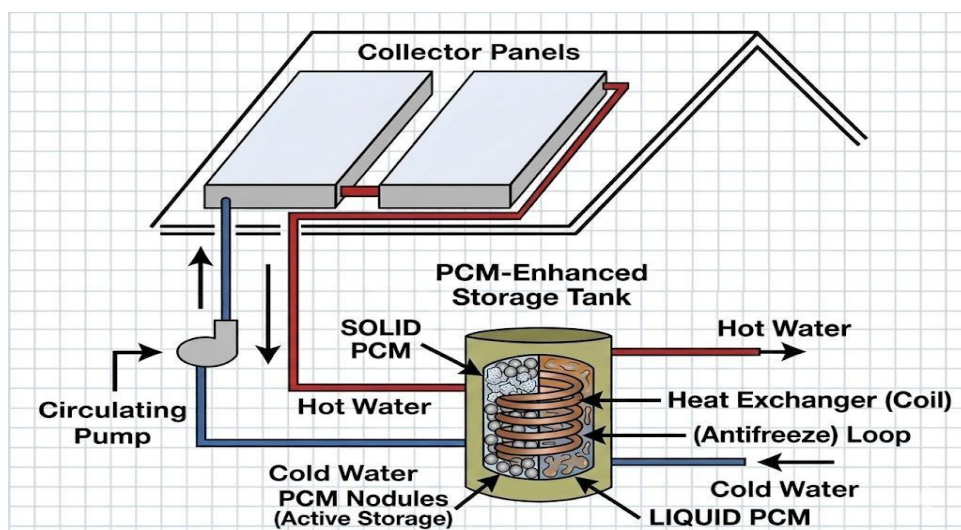


Figure II.5: Phase Change Material (PCM) Storage Tank

### 2.2.6 Large-Scale / Seasonal Thermal Energy Storage (STES)

Large-scale or seasonal thermal energy storage systems as shown in figure II.6, are designed for long-term storage of thermal energy. These systems use large steel or concrete tanks, or underground pit thermal energy storage structures, to store excess solar heat during summer for use in winter. STES technologies can greatly reduce fossil fuel consumption and improve long-term energy efficiency in district heating and industrial applications. However, they require high initial investment costs and large installation areas, which limits their use to large-scale energy systems and industrial facilities [2], [10], [14].

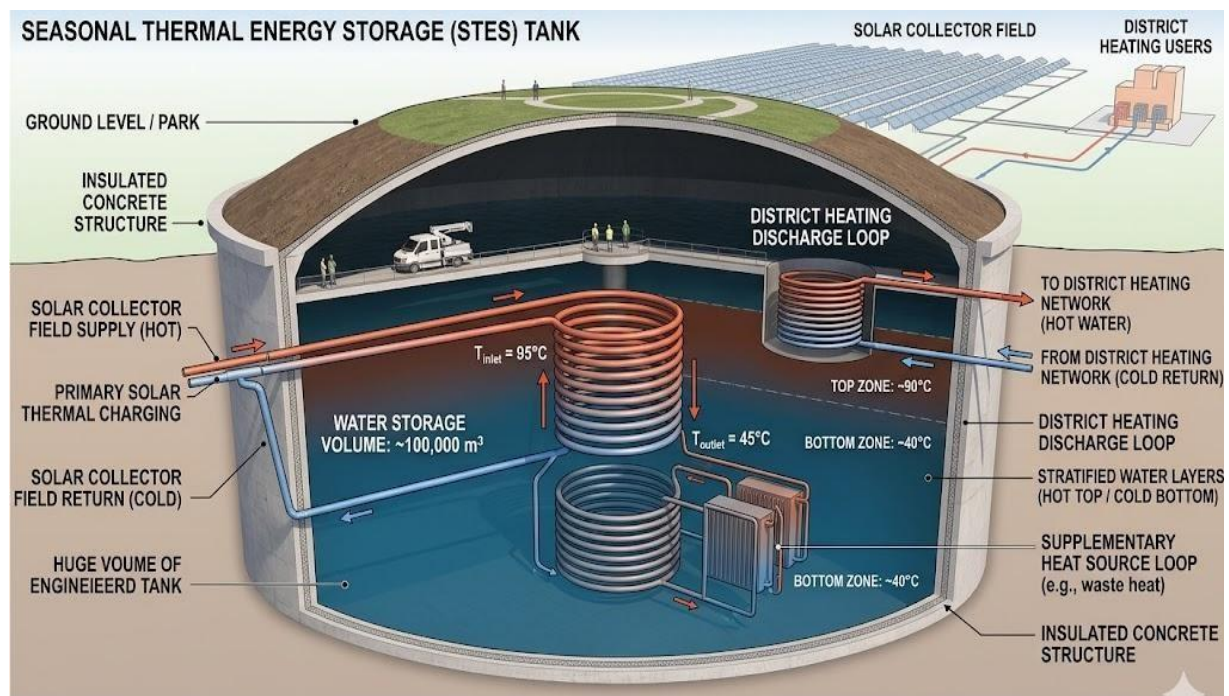


Figure II.6: Large-Scale / Seasonal Thermal Energy Storage (STES)

Stratified storage tank (SST) associated with a solar thermal system was selected for this study.

## 2.3 Explanation of the SST associated with a FPSC

### 2.3.1 System description

The system consists of a primary solar collection loop and a secondary storage/distribution loop. The "forced circulation" aspect implies that a pump is used to move the fluid as shown in figure II.4, allowing the tank to be placed anywhere (e.g., in a basement) regardless of the collector's height [3], [10].

### 2.3.1.1 Components Description

#### 2.3.1.1.1 The Flat-Plate Collector (FPC) Unit:

The collector is the heat-generating component. As shown in figure II.4, its configuration includes: [10], [13]

- **Glazing (Cover):** Typically made of a single or double layer of high-transmittance, low-iron tempered glass. It reduces convective and radiative heat losses to the atmosphere by trapping long-wave radiation (the greenhouse effect) [10], [13].
- **Absorber Plate:** A metallic sheet (usually copper or aluminum) with a selective coating (like Black Chrome or tinnox). This coating is engineered to have high solar absorptivity ( $\alpha > 0.95$ ) and low thermal emissivity ( $\epsilon < 0.1$ ) [10].
- **Flow Network (Risers and Headers):**

**Risers:** Smaller vertical tubes thermally bonded to the absorber plate.

**Headers:** Larger horizontal pipes at the top and bottom that distribute the fluid to and from the risers.

- **Insulation:** High-temperature resistant materials (glass wool or polyurethane foam) line the back and sides of the casing to minimize conductive heat loss [13]

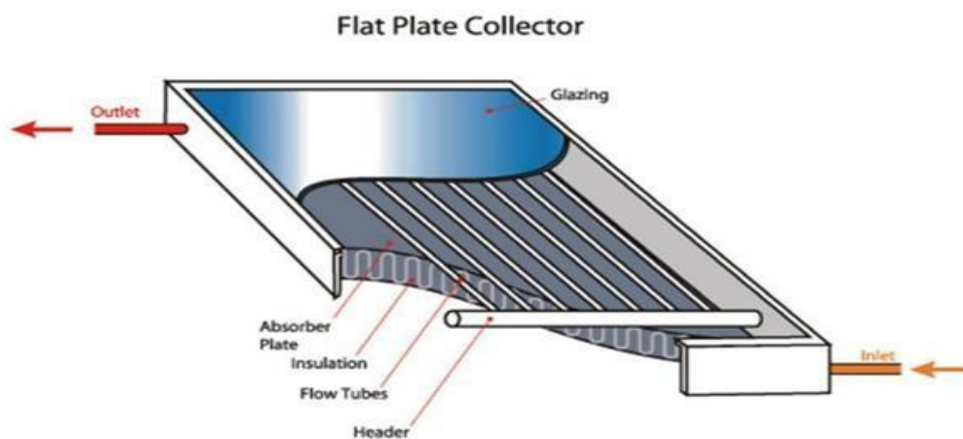


**Figure II.7:** The Flat-Plate Collector (FPC) Unit

#### 2.3.1.1.2 The Stratified Storage Tank Configuration

In high-efficient systems, the tank is designed to maintain **thermal stratification**, where water is layered by density variation due to temperature difference [1], [11], [17], [20]. **the tank geometry should be a** vertical cylindrical shape. A high aspect ratio (height-to-diameter) promotes better separation between the hot and cold layers [6], [11], [20]. **Inlet**

**diffusers** which are critical components located at the entry points. They reduce the velocity of the incoming fluid and distribute it horizontally. This prevents ‘**flow suction**’ and **mixing (destratification)**, ensuring that the hot water from the collector sits quietly on top of the cooler water [9], [18], [20]. Then the **internal Zoning which is divided as following:**

**3.1. Top Zone (Auxiliary/Delivery):** Where the hottest water is stored for immediate use. An auxiliary heater (electric or gas) is often placed here to guarantee a set temperature.

**3.2. Thermocline (Gradient Layer):** A thin transition region with a steep temperature gradient that acts as a barrier between hot and cold zones.

**3.3. Bottom Zone (Return):** Contains the coolest water, which is sent back to the solar collector [1], [11].

#### *1.1.1.1.2 Fluid Handling Components*

The fluid handling components manage the circulation of the heat transfer fluid (HTF) between the solar collector and the thermal storage tank. This section includes a circulation pump installed on the cold fluid line ( $T_{co,in}$ ) to push the fluid through the piping loop and overcome friction. The pump is regulated by an electronic controller that responds to temperature differences between the collector and the tank. These components ensure that hot fluid from the collector ( $T_{co,out}$ ) enters the top of the tank (Layer 1) to preserve thermal stratification, while cold water from the bottom (Layer N) is drawn back into the collector to be reheated.

#### *2.3.1.2 Operating Principle*

The working principle is based on three modes as follows:

1. **Charging Mode:** This mode governs system behavior during periods of sufficient solar irradiance, where harvested energy is actively packed into the storage reservoir **by accumulation**.
2. **Discharging Mode:** This mode occurs in the absence of solar irradiance when the tank delivers thermal energy to the load
3. **Standby Mode:** This represents the passive mode where no charging or discharging mode happened.

## 2.4 Conclusion :

In summary, the detailed analysis in this chapter highlights that an efficient solar thermal system requires a perfect match between heat collection and heat storage. The FPC acts as the primary tool to absorb solar energy, while the vertical SST ensures this energy is saved efficiently by preventing hot and cold-water layers from mixing. By controlling the forced circulation of the HTF through a pump and a controller, the system avoids heat losses and maintains steady operation during all modes. These working principles establish the clear technical framework needed to analyze and improve the system's thermal performance.

### **3 Chapter III**

## **Theoretical Modeling and Algorithm**

### 3.1 Introduction :

Thermal energy storage plays a key role in improving the performance and reliability of solar thermal systems by reducing the mismatch between energy availability and energy demand. Among the various storage technologies, stratified water tanks are widely used because they allow thermal energy to be stored efficiently while preserving temperature gradients within the tank [1], [2], [11], [12].

The performance of a stratified storage tank depends strongly on the charging and discharging processes, the routing of incoming fluid streams, heat losses to the environment, and the preservation of thermal stratification. Because these phenomena are transient and highly coupled, experimental measurements alone are often insufficient to provide a complete understanding of the tank behavior under different operating conditions [4], [11], [17], [20].

Therefore, mathematical modeling and numerical simulation are essential tools for predicting the thermal response of storage tanks and evaluating their performance. In this chapter, a one-dimensional multi-node stratified model based on the Duffie and Beckman approach is developed. The tank is discretized into several horizontal layers, and energy conservation is applied to each layer to describe the transient evolution of temperature during charging, discharging, and standby modes [1], [4], [12], [20].

The resulting system of governing equations is solved numerically using the explicit Euler method and implemented in MATLAB. The developed computational algorithm enables the simulation of thermal stratification, useful charging and discharging power, and the overall thermal behavior of the storage tank under realistic operating conditions [5], [22].

### 3.2 General Thermodynamic Energy Balance

The operation of a stratified thermal storage tank is governed by the first law of thermodynamics. The thermal energy accumulated within the tank is determined by the balance between energy entering the tank, energy leaving the tank, and heat losses to the surroundings [13].

$$\frac{dE}{dt} = \dot{Q}_{in} - \dot{Q}_{out} + \dot{Q}_{gen} - \dot{Q}_{loss} \quad (III.1)$$

Where

$Q_{in}$  :Rate of heat transfer into the system.

$Q_{out}$  : Rate of heat transfer out of the system.

$Q_{gen}$ : Rate of heat generation inside the system.

$Q_{loss}$ : Rate of heat loss

$\frac{dE}{dt}$ ; represents the rate of energy accumulation within the layer

In a stratified storage tank, thermal energy is stored as sensible heat within the water volume. The thermal energy contained in a layer of mass  $m_i$  and temperature  $T_i$  is given by:

$$E_i = m_i c_p T_i \text{ (III.2)}$$

where  $C_p$  is the specific heat capacity of water.

separation creates a vertical temperature gradient:  $T_{TOP} > T_{middle} > T_{bottom}$  .[1], [11], [17], [18]

which improves the thermal performance of the storage system by preserving high-temperature water at the top for load supply and low-temperature water at the bottom for efficient heat collection [1], [11].

The thermal behavior of the tank is mainly influenced by three heat-transfer mechanisms: [13]

- Convective transport associated with mass flow during charging and discharging processes.
- Heat transfer between adjacent layers caused by temperature differences within the tank.
- Heat losses through the tank walls to the surrounding environment.

These thermodynamic principles constitute the physical foundation of the stratified multi-node model developed in the following sections [1], [13].

To simulate the thermal behavior of the solar water storage tank, a 1D stratified multi-node modeling approach is selected. This method provides the necessary accuracy to capture the vertical

thermal stratification layers and the temperature gradient (thermocline) across the tank during charging and discharging modes, while maintaining high computational efficiency suitable for dynamic system simulations [1], [12], [20].

### 3.3 Duffie Multi-Node Approach

By adopting the Duffie and Beckman formulation, this modeling choice results in a coupled system of  $N$  ordinary differential equations. Because these equations track complex, time-dependent fluid routing between the flat-plate solar collector loop and the user thermal load. This framework serves as the exact mathematical foundation for the computer-driven numerical solver developed in this study to simulate real-world, transient operational conditions [1], [12], [20].

Figure III.1 illustrates the schematic of this approach, where the tank is discretized into  $N$  horizontal layers.

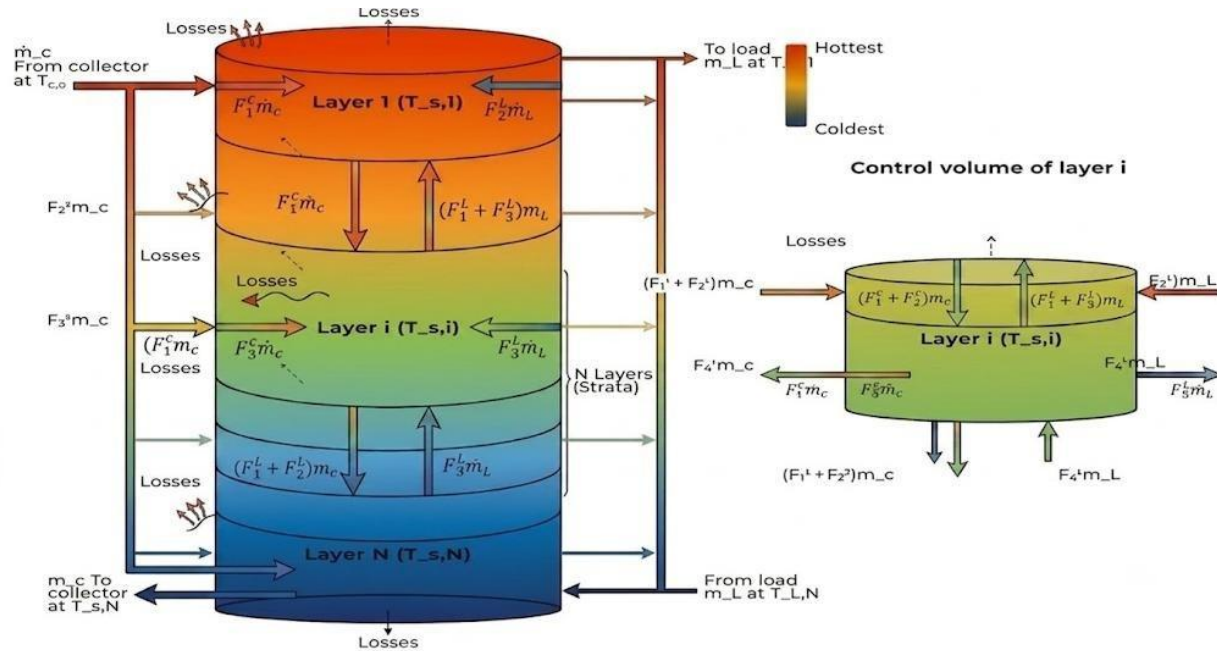


**Figure III.1:** Schematic of the Duffie and Beckman multi-node stratified storage tank

The tank contains several layers that are treated independently. As shown in figure III.1, the detailed view of "Layer i," represent the control volume segment in which the energy balance is applied to each layer.

### 3.3.1 Control function

To prevent artificial mixing and accurately simulate thermal stratification, fluid entering the tank from external loops must be directed to a layer matching its temperature. As shown in **figure III.1**, this routing is achieved using control functions that dictate which specific layer interacts with the incoming or outcoming stream [1], [9], [18].

**Collector Loop Integration:** Fluid returning from the collector at temperature  $T_{co}$  is directed to a matching layer by the collector return control function  $F_t^c$ :

$$F_t^c = \begin{cases} 1 & \text{if } i = 1 \text{ and } T_{co} > T_{s,i} \\ 1 & \text{if } T_{s,i} \geq T_{co} > T_{s,i-1} \\ 0 & \text{if } i = 0 \text{ or } i = N + 1 \\ 0 & \text{otherwise} \end{cases} \quad (\text{III.3})$$

**Load Loop Integration:** Fluid returning from the load loop at temperature  $T_{L,r}$  (or  $T_{L,N}$ ) is routed to the appropriate lower section via the load return control function  $F_t^{Lr}$ :

$$F_t^{Lr} = \begin{cases} 1 & \text{if } i = N \text{ and } T_{L,r} > T_{s,N} \\ 1 & \text{if } T_{s,i-1} \geq T_{L,r} > T_{s,i} \\ 0 & \text{if } i = 0 \text{ or } i = N + 1 \\ 0 & \text{otherwise} \end{cases} \quad (\text{III.4})$$

### 3.3.2 Advection Net mass Flows Rate $\dot{m}_{m,i}$

As visualized in the detailed "control volume of layer i" breakout in **figure III.1**, net flow between nodes can be either up or down depending upon the magnitudes of the collector and load flow rates and the values of the two control functions at any particular instant. It is convenient to define a mixed-flow rate that represents the net flow into node i from node i-1, excluding the effects of flow, if any, directly into the node from the load:

- **Flow Direction Convention:** A positive value ( $\dot{m}_{m,i} > 0$ ) indicates downward net mass transport from layer i-1 into layer i. A negative value ( $\dot{m}_{m,i} < 0$ ) indicates upward net mass transport

$$\dot{m}_{m,i} = \dot{m}_c \sum_{j=1}^{i-1} F_j^c - \dot{m}_L \sum_{j=i+1}^N F_j^L \quad (\text{III.5})$$

Where the strict boundary conditions are defined as  $\dot{m}_{m,i=0} = 0$  and  $\dot{m}_{m,N+1} = 0$  (III.6)

### 3.3.3 Duffie and Beckman Energy Balance equation:

For a control volume representing a storage layer, the general energy conservation equation can be expressed as:

$$m_i \frac{dT_{s,i}}{dt} = Q_{\text{loss}} + Q_{\text{load}} + Q_{\text{collector}} + Q_{\text{adv}} \quad (\text{III.7})$$

Applying the conservation of energy to a single node  $i$ , the transient thermal profile is governed by: (III.8)

$$m_i \frac{dT_{s,i}}{dt} = \left( \frac{UA}{C_p} \right)_i (T_{a'} - T_{s,i}) + F_c \dot{m}_c (T_{co} - T_{s,i}) + F_L \dot{m}_L (T_{L,r} - T_{s,i}) + Q_{adv}$$

Where the conditional advective transport term  $Q_{adv}$  dynamically shifts its dependence to reflect the directional behavior of the fluid columns:

$$\begin{cases} Q_{adv} = \dot{m}_{m,i} (T_{s,i-1} - T_{s,i}) & \text{if } \dot{m}_{m,i} > 0 \\ Q_{adv} = \dot{m}_{m,i+1} (T_{s,i} - T_{s,i+1}) & \text{if } \dot{m}_{m,i+1} < 0 \end{cases} \quad (\text{III.9})$$

Where

$m_i$  : Mass of the fluid inside node  $i$  (measured in kg).

$T_{s,i}$  : Temperature of the fluid inside node  $i$  (C or K).

$t$ : Time (measured in seconds, s).

$\frac{dT_{s,i}}{dt}$  : Time rate of change of temperature in node  $i$ .

$U$ : Overall heat transfer coefficient of the tank wall ( $\text{W}/\text{m}^2\cdot\text{K}$ ).

$A$ : Surface area of the tank wall corresponding specifically to node  $i$  ( $\text{m}^2$ ).

$C_p$ : Specific heat capacity of the fluid ( $\text{J} / \text{Kg}\cdot\text{K}$ ).

$T_a$ : Ambient (surrounding) temperature outside the tank.

$F_c$ : Collector control function (a binary switch: 1 or 0). It dictates whether the hot fluid returning from the solar collector is entering this specific node  $i$ .

$\dot{m}_c$ : Mass flow rate of the fluid circulating through the solar collector ( $\text{kg}/\text{s}$ ).

$T_{co}$ : Collector outlet temperature (C or K); this is the hot fluid entering the tank from the collector.

$F_t^L$ : Load control function (binary switch: 1 or 0). It dictates whether the colder fluid returning from the load (utility/heating system) is entering this specific node  $i$ .

$\dot{m}_L$ : Mass flow rate of the fluid circulating through the load loop (kg/s).

$T_{L,r}$ : Load return temperature (C °); this is the temperature of the fluid coming back into the tank after dropping off its heat to the building or process.

### 3.3.3.1 Node Temperature Calculation

Using the forward explicit Euler approximation across a time interval  $\Delta t$ , the temporal left side term can be expressed as:

$$\frac{dT_{s,i}}{dt} = \frac{T_{s,i}^{new} - T_{s,i}^{old}}{\Delta t} \quad (\text{III.10})$$

By replacing in Eq : (III.8), the new temperature is evaluated directly from known (old) temperature values as: [1]. (III.11)

$$T_{s,i}^{new} = T_{s,i}^{old} + \frac{\Delta t}{m_i} \left( \left( \frac{UA}{C_p} \right) (T_a - T_{s,i}) + F_c \dot{m}_c (T_c - T_{s,i}) + F_t^L \dot{m}_l (T_{L,r} - T_{s,i}) + Q_{adv} \right)$$

Where the active numerical advection parameter is structured via code logic:

$$\text{if } \dot{m}_{m,i} > 0: Q_{adv} = \dot{m}_{m,i} (T_{s,i-1} - T_{s,i})$$

$$\text{if } \dot{m}_{m,i+1} < 0: Q_{adv} = \dot{m}_{m,i+1} (T_{s,i} - T_{s,i+1})$$

### 3.3.3.2 System Operating Modes

#### 3.3.3.2.1 Charging Mode

Charging mode occurs when the temperature of the heat source  $T_{co}$  exceeds the temperature of the uppermost layer of the storage tank  $T_{s,N}$ , and the charging mass flow rate  $\dot{m}_c$  is positive. Under these conditions, hot fluid enters the tank and is directed to the thermally stratified layer  $i$  that corresponds to its temperature. A binary activation flag  $F_t^c$  is set to 1 for the matching layer  $i$ . The energy contribution associated with charging is expressed by the following term in the governing energy equation: [1], [10]

$$+ F_t^c \dot{m}_c C_p (T_{co} - T_{s,i}) \quad (\text{III.12})$$

This term represents the rate of thermal energy addition to layer  $i$ . Its magnitude is determined by the product of the charging flow rate, the specific heat capacity of the fluid, and the local temperature difference between the incoming fluid and the receiving layer. Consequently, the temperature of layer  $i$  increases, and thermal energy is subsequently redistributed to adjacent layers via conduction and natural convection [13].

### 3.3.3.3 Discharging Mode

Discharging mode is activated when a hot water demand exists ( $\dot{m}_L > 0$ ) and the temperature of the top layer  $T_{s,1}$  is greater than the return water temperature from the load  $T_{Lr}$ . In this mode, hot water is extracted from the tank (typically from the upper region) to satisfy the load, while cooler water returns to the tank and settles into the layer  $i$  that matches its temperature. The binary flag  $F_i^{Lr}$  is set to 1 for that layer. The energy term introduced into the governing equation is: [1], [17], [18]

$$+F_i^{Lr} \dot{m}_L C_p (T_{Lr} - T_{s,i}) \quad (\text{III.13})$$

Since the return temperature  $T_{Lr}$  is generally lower than the layer temperature  $T_{s,i}$  due to heat extraction by the load, the temperature difference is negative. Hence, this term represents a net energy removal from layer  $i$ , leading to a local decrease in temperature and overall cooling of the storage tank [13].

### 3.3.3.4 Standby Mode

Standby mode occurs when both the charging and discharging mass flow rates are zero:  $\dot{m}_c = 0$  and  $\dot{m}_L = 0$ . Under these conditions, no fluid enters or leaves the tank. Both activation flags are set to zero for all layers:  $F_i^c = 0$  and  $F_i^{Lr} = 0$  for all  $i$ . Consequently, the energy equation simplifies to include only the heat loss term to the ambient environment: [1], [21]

$$Q_{loss} = (UA)_i (T_a - T_{s,i}) \quad (\text{III.14})$$

Here,  $(UA)_i$  denotes the overall heat transfer coefficient–area product for layer  $i$ , and  $T_a$  is the ambient air temperature. Given that  $T_a$  is typically less than  $T_{s,i}$ , the heat loss term is negative,

indicating a continuous reduction in thermal energy. Thus, during standby, the tank undergoes gradual self-discharge due to thermal dissipation through its insulation and walls, until thermal equilibrium with the surroundings is approached [13], [21].

### 3.3.4 Useful Power Calculations

To evaluate the thermal performance of the system, the useful thermal power received and delivered during operation is calculated using the following expressions [1], [10], [13].

- Useful power in charging (from the collector to the tank)  $Q_{uc}$

$$Q_{uc} = \sum_{t=1}^{end} (\dot{m}_c C_p (T_{co} - T_{s,i})) \quad \text{only if } (T_{co} > T_{s,i}) \quad (\text{III.15})$$

where

$Q_{uc}$ : is the useful charging power (W),

$\dot{m}_c$ : is the collector loop mass flow rate (kg/s),

$C_p$ : is the specific heat capacity of the working fluid (J/kg·K),

$T_{co}$ : is the collector outlet temperature (°C or K),

$T_{s,i}$ : is the temperature of the considered storage tank layer  $i$  during the charging process (°C or K).

- Useful power in discharging (from the tank to the load)  $Q_{ud}$

$$Q_{ud} = \sum_{t=1}^{end} (\dot{m}_L C_p (T_{s,i} - T_{Lr})) \quad \text{only if } (T_{s,i} > T_{Lr}) \quad (\text{III.16})$$

where

$Q_{ud}$ : is the useful discharging power (W),

$\dot{m}_L$ : is the load-side mass flow rate (kg/s),

$C_p$ : is the specific heat capacity of water (J/kg·K),

$T_{Lr}$ : is the load return temperature entering the tank (°C or K),

$T_{s,i}$ : is the temperature of the considered storage tank layer  $i$  during the discharging process (°C or K).

### 3.4 State assumptions/limitations

To implement a computationally viable numerical model, specific underlying assumptions and system boundaries have been established in accordance with the principles outlined [1], [12], [13]

#### 3.4.1 Assumptions

**One-Dimensional Stratification Profile:** Temperature distributions occur exclusively along the vertical axis of the tank, moving from the hottest zone at Layer 1 down to the lowest/coldest zone at Layer N as diagrammed in **figure [III.1]**. Radial temperature gradients within any single discrete layer are assumed to be negligible (fully mixed node assumption) [1], [12], [20].

**Idealized Stratification Management:** Incoming fluids are assumed to enter their thermally matching strata smoothly without prompting turbulent plume entrainment or mixing in neighboring layers. This represents the behavior of an optimized, low-velocity manifold system like the one physically visualized via dyed water testing **from Buffie and Beckman book** [1], [6], [9].

**Constant Thermophysical Properties:** The specific heat capacity ( $C_p$ ) and density of the working fluid are assumed uniform and constant across the operational temperature range of all layers [13].

#### 1.1.1.2 Limitations

**Sensitivity to Discretization (N):** The accuracy of the simulated thermal gradient is heavily dependent on the chosen number of layers (N). A low value of N introduces numerical diffusion, which artificially flattens the temperature profile and understates the tank's true thermodynamic performance potential [19], [20].

**Simplification of Physical Geometry:** While the real-world degree of stratification depends heavily on the physical dimensions, location, and flow velocities of the physical inlets and outlets, this multi node framework reduces complex fluid dynamics into localized thermodynamic control volumes [4], [12], [20].

### 3.5 Development of the Algorithm

The mathematical model developed in the previous sections was implemented in MATLAB in order to simulate the transient thermal behavior of the stratified storage tank. The objective of the MATLAB program is to solve the system of coupled energy balance equations for the five tank layers and to evaluate the temperature evolution, useful charging power, useful discharging power, and stored thermal balance during the complete operating cycle [22].

The implemented model is based on a one-dimensional multi-node approach. The storage tank is divided into five horizontal layers, where each layer is considered as a fully mixed control volume with a uniform temperature. The temperature variation in each layer is calculated using the explicit Euler method with a constant time step of 60 seconds [1], [12], [20], [22].

The simulation includes three operating modes: charging mode, discharging mode, standby mode.

The selection of the operating mode is performed automatically at each time step, as function of the collector temperature, layer temperature, and load charge [22].

### 3.5.1 MATLAB Program Structure

The MATLAB code is organized into several main parts, allows each physical phenomenon to be treated separately [22].

The general structure of the program is as follows:

1. Clear workspace and initialize parameters
2. Define tank geometry and physical properties
3. Define simulation time and operating periods
4. Define collector temperature data
5. Initialize tank layer temperatures
6. Start the time-marching loop
7. Interpolate collector temperature
9. Apply charging, discharging, or standby equations based on the condition
10. Update tank layer temperatures
11. Save simulation results
12. Display numerical results
13. Plot graphical results

### 3.5.2 Initialization of Parameters (Input data)

At the beginning of the MATLAB program, all physical, geometrical, and numerical parameters are defined. [22]

The simulation time step is fixed as:

$$\Delta t = 60 \text{ s}$$

The tank is characterized by a height:

$$H = 2 \text{ m}$$

a radius:

$$r = 0.3 \text{ m}$$

and it is divided into:

$$N = 5 \text{ horizontal layers.}$$

The water properties are assumed constant during the simulation. The density and specific heat capacity are given by:

$$\rho = 1000 \text{ kg/m}^3$$

$$C_p = 4180 \text{ J/kg.K}$$

The ambient temperature is assumed constant:

$$T_a = 20^\circ\text{C}$$

The initial temperature of all tank layers is set to:

$$T_1 = T_2 = T_3 = T_4 = T_5 = 20^\circ\text{C}$$

The charging and discharging mass flow rates are defined respectively as:

$$\dot{m}_c = 0.03 \text{ kg/s}$$

$$\dot{m}_l = 0.02 \text{ kg/s}$$

The charging process is simulated from the beginning of the simulation until 11 hours, while the discharging process starts after the charging period and continues until the end of the simulation.

### 3.5.3 Tank Geometry Discretization

The tank is discretized into five equal horizontal layers. The height of each layer is calculated as:

$$Z = \frac{H}{N}$$

The lateral heat transfer area of each layer is:

$$A_i = 2\pi r Z$$

The mass of water contained in each layer is calculated by:

$$m_i = \pi r^2 Z \rho$$

These geometrical parameters are used in the energy balance equation of each layer. Since all layers have the same height, each layer has the same mass and lateral heat transfer area.

#### 3.5.3.1 Collector Temperature Data and Interpolation

The collector outlet temperature  $T_c$  is introduced in the MATLAB program as a vector of experimental or predefined values. These values are given at intervals of 10 minutes [22].

However, the numerical simulation is performed with a time step of 60 seconds. Therefore, linear interpolation is used to calculate the collector temperature at every simulation time step. This avoids sudden discontinuities in the collector temperature and provides a smoother thermal response [22]. The interpolation is written in using MATLAB:

During the discharging period, the collector loop is not active. Therefore, the displayed collector temperature is set to zero in the output table and figures.

#### 3.5.3.2 Operating Mode Selection

At each time step, the MATLAB program determines the operating mode of the tank. Three possible modes are considered [1], [22].

### 3.5.3.2.1 Charging Mode

Charging mode is activated during the charging period when the collector temperature is higher than the temperature of the bottom tank layer: [1], [22]

$$T_c \geq T_N$$

In this case, the collector mass flow rate is activated:

$$\dot{m}_c = 0.03 \text{ kg/s}$$

and the load mass flow rate is set to zero:

$$\dot{m}_l = 0$$

The mode is stored in the program as:

$$mode = 1$$

### 3.5.3.2.2 Discharging Mode

- Discharging mode is activated after the charging period when the temperature of the top layer is greater than the discharge stop temperature: [1], [22]

$$T_1 > T_{stop}$$

- In this case, the collector loop is closed:

$$\dot{m}_c = 0$$

- and the load mass flow rate is activated:

$$\dot{m}_l = 0.02 \text{ kg/s}$$

- The mode is stored as:

$$mode = 2$$

### 3.5.3.2.3 Standby Mode

Standby mode occurs when neither charging nor discharging conditions are satisfied. In this case: [1], [21], [22]

$$\dot{m}_c = 0$$

$$\dot{m}_l = 0$$

Only heat losses to the ambient environment are considered. The mode is stored as:

$$mode = 0$$

### 3.5.4 Charging Mode Implementation

During charging mode, the program calculates the collector control factor  $F_c(i)$ . This factor determines the tank layer that receives the hot fluid coming from the collector [1], [9], [22].

Eq (III.3).

The MATLAB code checks the temperature position of the collector fluid with respect to the temperature of each layer. If the collector temperature is suitable for a given layer, the corresponding value of  $F_c(i)$  is set to 1 [1], [22].

The useful charging power is calculated as Eq (III.15): [1], [10], [13]

This expression is applied only when:

$$T_c > T_i$$

The temperature of each layer is then updated using the energy balance equation: [1], [13]

$$T_{s,i}^{new} = T_{s,i}^{old} + \frac{\Delta t}{m_i} (Q_{loss} + Q_{collector} + Q_{mixing})$$

where the heat loss term is: Eq (III.14)

and the collector heat input is: Eq (III.12)

The mixing term  $Q_{mixing} = Q_{adv}$  represents the thermal effect of the net flow between adjacent layers [1], [12]. Eq (III.9)

### 3.5.5 Discharging Mode Implementation

During discharging mode, the load control factor  $F_l(i)$  is calculated. This factor determines the layer where the cold return water from the load enters the tank [1], [9], [22].

The load control factor is defined as: Eq (III.4)

The useful discharging power is calculated from the top layer because hot water is extracted from the upper part of the tank Eq (III.16): [1], [10]

This expression is applied only when:

$$T_1 > T_l$$

The temperature of each layer during discharging is updated according to: [1], [13]

$$T_{s,i}^{new} = T_{s,i}^{old} + \frac{\Delta t}{m_i} (Q_{loss} + Q_{load} + Q_{mixing})$$

where the load term is:Eq (III.13):

Since the return temperature  $T_l$  is lower than the tank temperature, this term generally has a negative effect and represents heat removal from the storage tank [13].

### 3.5.6 Standby Mode Implementation

In standby mode, both the collector and load loops are inactive. There fore :

$$\dot{m}_c = 0$$

$$\dot{m}_l = 0$$

The temperature variation of each layer is only caused by heat losses to the surrounding environment :

$$T_{s,i}^{new} = T_{s,i}^{old} + \frac{\Delta t}{m_i} Q_{loss}$$

This mode represents the natural cooling of the storage tank when there is no energy input and no useful energy extraction [21].

### 3.5.7 Inter-Layer Mixing Flow

The MATLAB program also calculates the net mass flow rate between the tank layers. This internal flow is represented by : [1], [12]

$$\dot{m}_{m,i}$$

During charging, the net flow depends on the activated collector control function. During discharging, it depends on the position of the active load return layer.

The mixing heat transfer term is calculated according to the direction of the internal flow. If the flow is downward, the layer receives energy from the upper layer. If the flow is upward, the thermal interaction occurs with the lower layer [1], [12], [20].

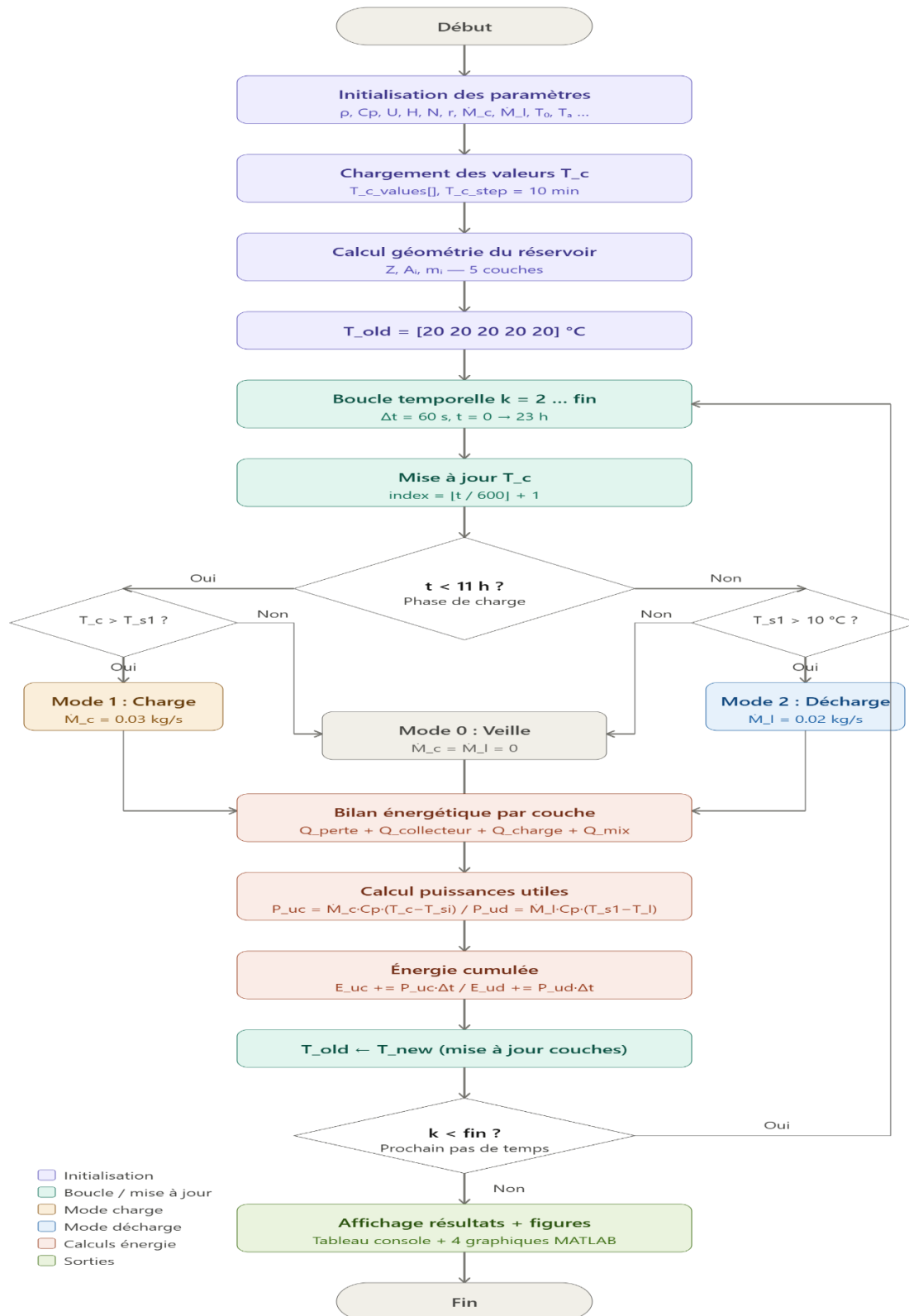
This implementation allows the model to account for the displacement of water inside the tank while preserving the stratified structure.

### 3.5.8 Temperature Update Using the Explicit Euler Method

The system of energy balance equations is solved using the forward explicit Euler method. At each time step, the new temperature of each layer is calculated directly from the known temperature at the previous time step [22].

The general numerical form is: Eq (III.11)

## 3.5.9 organization char



### 3.6 Conclusion

This chapter presented the theoretical development, numerical formulation, and MATLAB implementation of a stratified thermal storage tank model. Starting from the fundamental principles of energy conservation, a one-dimensional multi-node approach based on the Duffie and Beckman formulation was adopted to describe the transient thermal behavior of the storage tank.

The governing energy balance equations were established for each layer by considering heat addition from the solar collector loop, heat extraction by the load loop, inter-layer fluid transport, and thermal losses to the surrounding environment. Control functions were introduced to direct incoming fluid streams to the thermally appropriate layers, thereby preserving thermal stratification and reducing artificial mixing.

The resulting set of coupled differential equations was discretized using the explicit Euler method and implemented in MATLAB through a structured computational algorithm. In addition, expressions for useful charging and discharging power were incorporated to evaluate the thermal performance of the storage system.

The developed model provides a practical and computationally efficient framework for predicting temperature evolution, stratification quality, and energy transfer within the storage tank. The next chapter presents the simulation results and discusses the thermal performance of the system under the selected operating conditions.

## **4 Chapter IV**

### **Résulte and Discussion**

## 4.1 Introduction

This chapter provides the results of numerical simulations that were carried out using the previously created MATLAB model of the stratified hot-water storage tank. The storage tank thermal stratification phenomenon is modeled in detail using five layers placed horizontally to calculate the temperature distribution. The collector temperature is introduced as well as the other input data to the model, where, the three operating modes (charging....) depending on the input and inside storage tank temperatures.

In the first part of the chapter, the base-case simulation is provided for further comparison. The results such as the temperature variation of the five layers of the tank, , useful charging power, and useful discharging power were analyzed. The base-case is provided as a reference to the other simulation cases.

In the second part, a parametric study is performed for several operating conditions, such as the charging mass flow rate, discharging mass flow rate, tank water capacity, and the overall heat loss coefficient.

## 4.2 Base-case résultat

The base-case simulation is first performed using the reference operating parameters defined in the MATLAB model. This case is used as reference and the geometrical and thermal are introduced in Table IV.1.

**Table IV.1:** Base-case simulation parameters

| Parameter                  | Symbol         | Base value | Unit                |
|----------------------------|----------------|------------|---------------------|
| Tank height                | H              | 2          | m                   |
| Tank radius                | r              | 0.3        | m                   |
| Number of layer            | N              | 5          | -                   |
| Heat loss coefficient      | U              | 0.525      | W/m <sup>2</sup> .K |
| Ambient temperature        | T <sub>a</sub> | 20         | °C                  |
| Load return temperature    | T <sub>l</sub> | 20         | °C                  |
| Charging mass flow rate    | $\dot{m}_c$    | 0.03       | kg/s                |
| Discharging mass flow rate | $\dot{m}_L$    | 0.02       | Kg/s                |

**Figure IV.1** The following figure illustrates the evolution of the collector temperature and the temperatures of the five tank layers during the charging phase.

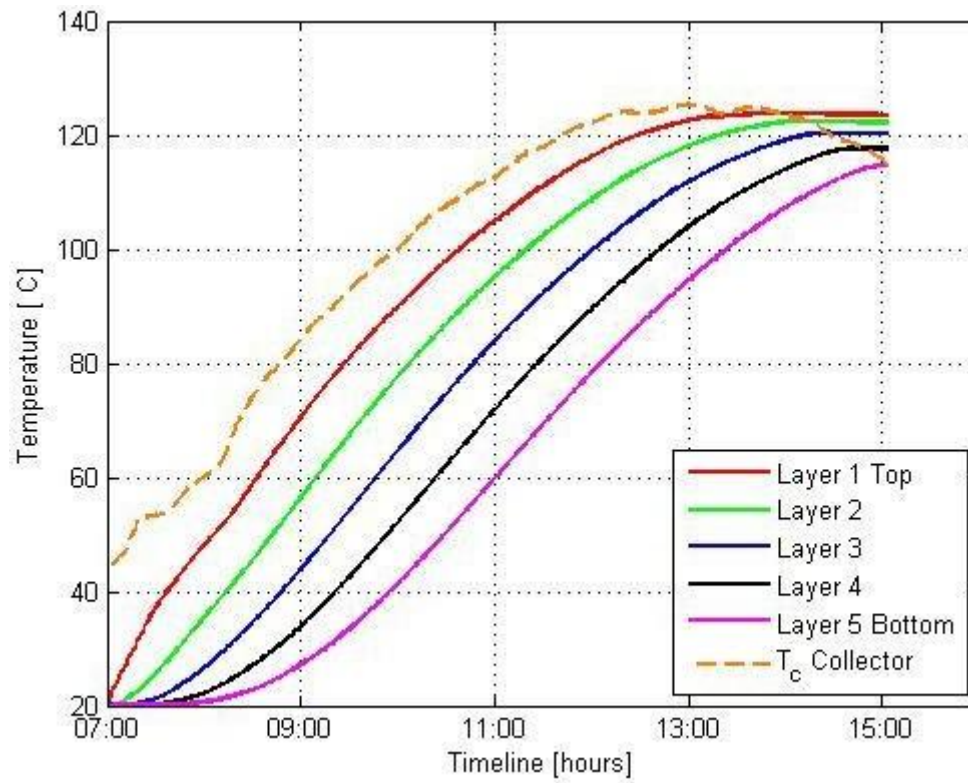


**Figure IV.1:** Tank Charging Temperature Evolution

At the beginning of the charging period, all the tank layers are close to the initial temperature of about 20 °C, while the collector temperature is already about 45 °C. From 07:00 to around 13:00, the collector temperature increases progressively and reaches nearly 125 °C. This rise is directly reflected in the upper part of the tank: Layer 1 increases from about 20 °C to approximately 120–124 °C, while the lower layers heat up with a clear delay. For example, around 09:00, Layer 1 is already near 60 °C, whereas Layer 5 is still only around 25–30 °C. This difference of about 30 °C confirms the existence of thermal stratification during charging. At the end of the charging period, around 15:00, the temperatures become closer: Layer 1 is about 123 °C, Layer 2 about 122 °C, Layer 3 about 120 °C, Layer 4 about 118 °C and Layer 5 about 115 °C. Therefore, the temperature difference between the top and bottom layers decreases to nearly 8 °C, which means that the tank approaches a nearly uniform high-temperature state after receiving sufficient solar heat.

**Figure IV.2:** This figure presents the temperature variation of the five tank layers during the discharging period

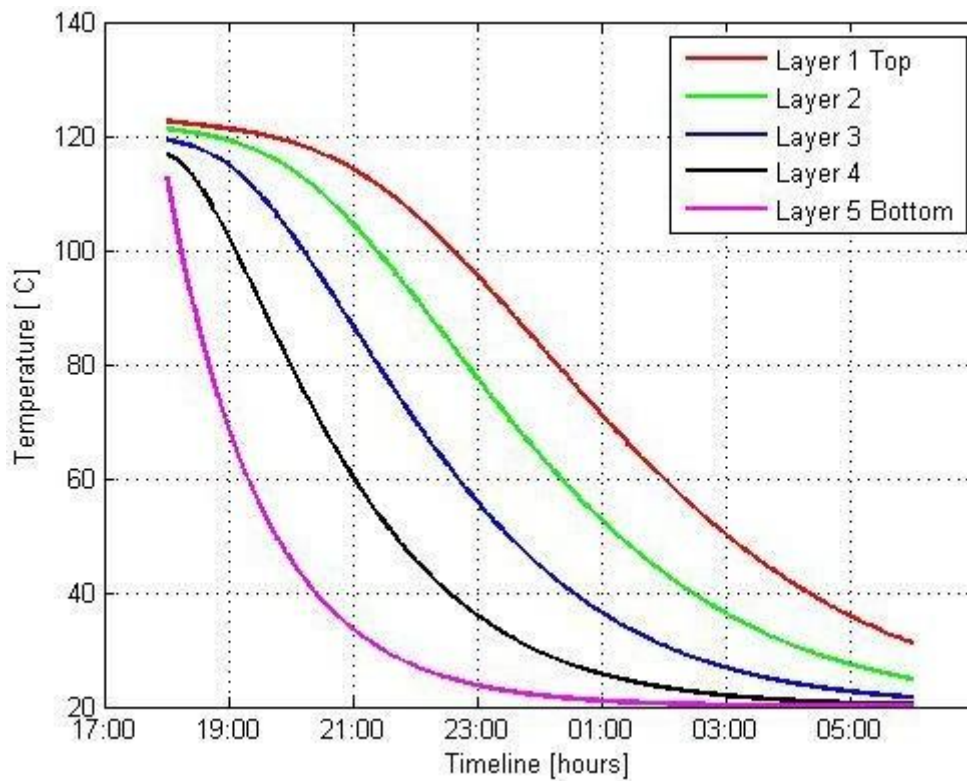


**Figure IV.2:** Tank Discharging Temperature Evolution

At the start of the discharging period, the tank is highly charged, with the top layer at about 122 °C and the bottom layer around 112 °C. Once the load starts, the bottom layer cools much faster because the cold return water enters the lower part of the tank. Layer 5 decreases from about 112 °C to nearly 60 °C around 19:00, then to about 35 °C around 21:00, and approaches 20–25 °C after 23:00. In contrast, the top layer remains hot for a longer time: it is still around 115 °C at 21:00, about 95 °C at 23:00, nearly 70 °C at 01:00, and around 35 °C near 05:00. This progressive cooling from the bottom to the top shows that the thermal front moves upward during discharging. The result confirms that stratification is beneficial because the upper part of the tank can continue supplying hot water even when the lower part has already cooled down.

**Figure IV.3:** The following figure combines the three operating periods of the storage tank: charging, standby and discharging.

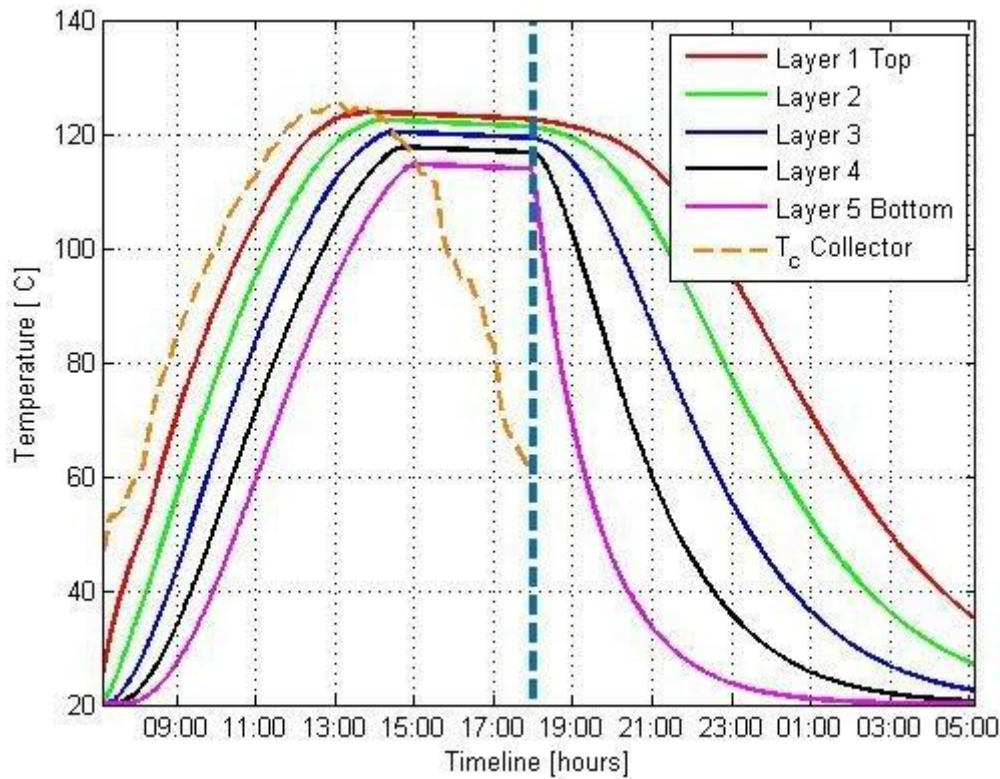


**Figure IV.3:** Tank Complete Thermal Behavior

This figure summarizes the complete thermal behavior of the tank. During the charging period, from about 07:00 to 15:00, the collector temperature rises from nearly 50 °C to a maximum value of about 125 °C, then starts to decrease before the discharging phase. The tank layers reach high temperatures before 18:00: the top layer is about 122–124 °C, Layer 2 about 121–122 °C, Layer 3 about 119–120 °C, Layer 4 about 116–118 °C and the bottom layer about 114–115 °C. The interval before the dashed vertical line represents the storage/standby period. During this period, the curves are almost horizontal, meaning that the heat losses are limited; the decrease is only a few degrees, especially in the upper layers. After the dashed line, around 18:00, discharging starts and the cooling becomes very clear. Layer 5 drops rapidly from about 114 °C to nearly 35 °C around 21:00, while Layer 1 decreases more slowly and remains above 90 °C until around 23:00. This behavior proves that the tank preserves useful heat at the top for several hours, while the lower part is affected first by the return water.

**Figure IV.4:** This figure shows the variation of the useful thermal power during charging and discharging.

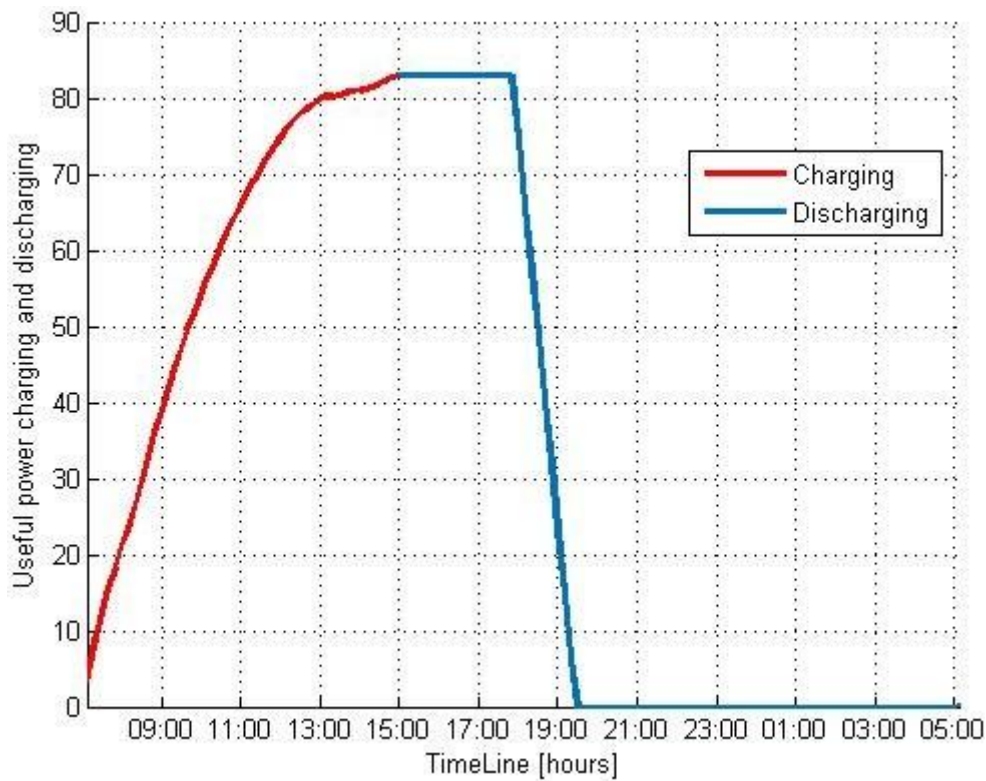


**Figure IV.4:** Tank Useful Thermal Balance

The useful thermal value during charging increases quickly at the beginning of the simulation. It starts from approximately 5 and reaches about 40 around 09:00, then about 65 around 11:00. Between 13:00 and 15:00, it approaches its maximum value, around 80–83, which indicates that the tank is close to its storage limit. From about 15:00 to 18:00, the curve remains almost constant at nearly 83, showing that the stored thermal capacity is maintained during the standby period. When discharging begins at about 18:00, the blue curve decreases sharply from approximately 83 to 0 between 18:00 and about 19:20. This means that the useful stored thermal quantity is consumed in nearly 1 hour and 20 minutes under the considered load conditions. After this time, the value remains close to zero until the end of the simulation, which indicates that the tank can no longer provide useful heat above the required load return temperature.

### 4.3 Parametric Study

#### 4.3.1 Effect of Charging Mass Flow Rate $\dot{m}_c$

In this case, the effect of the collector charging mass flow rate on the thermal behavior of the stratified storage tank is investigated. The charging mass flow rate is varied while all other parameters are kept constant in order to evaluate its influence on the heating rate, thermal stratification, and useful charging power.

**Figure IV.5 :** This figure shows the effect of the charging mass flow rate on the temperature of the top layer

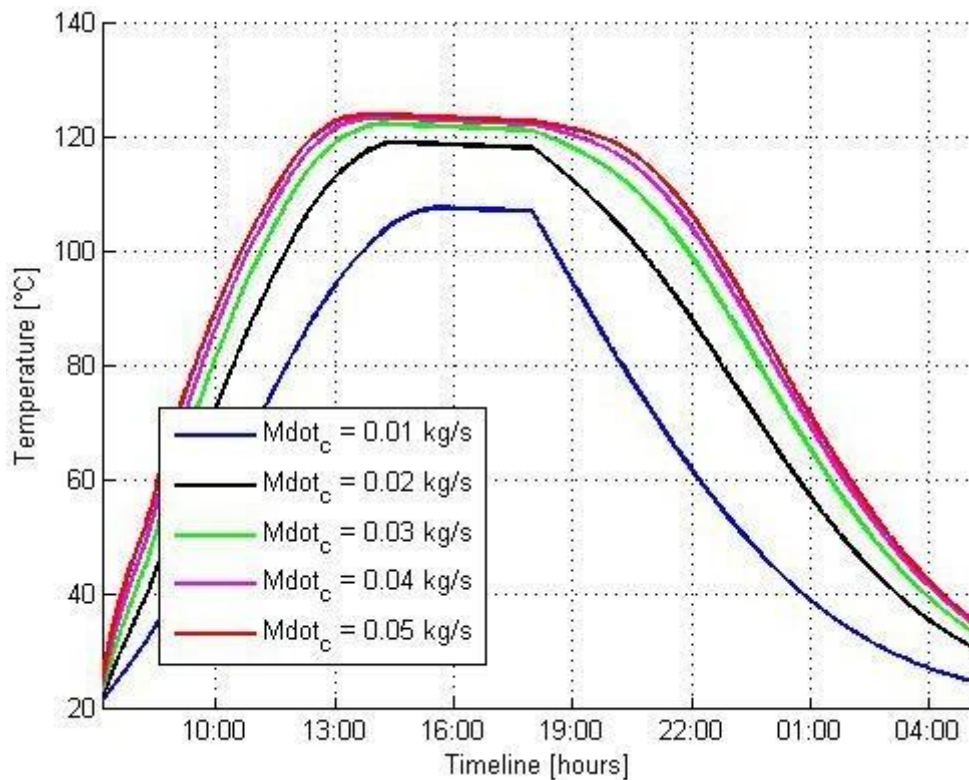


**Figure IV.5:** the evaluation of different  $\dot{m}_c$  on temperature on the top layer during the day

The top layer temperature increases for all charging mass flow rates, but the heating rate depends strongly on the value of  $\dot{m}_c$ . For the lowest flow rate, **0.01 kg/s**, the maximum top temperature is only about **107–108 °C**. When the flow rate increases to **0.02 kg/s**, the maximum temperature reaches nearly **119 °C**. For **0.03, 0.04, and 0.05 kg/s**, the top layer reaches about

**122–124 °C.** This shows that increasing the charging flow rate improves the heating of the upper layer. However, after **0.03 kg/s**, the improvement becomes small, since the curves of **0.03, 0.04, and 0.05 kg/s** are very close.

**Figure IV.6:** This figure illustrates the influence of the charging mass flow rate on the middle layer temperature

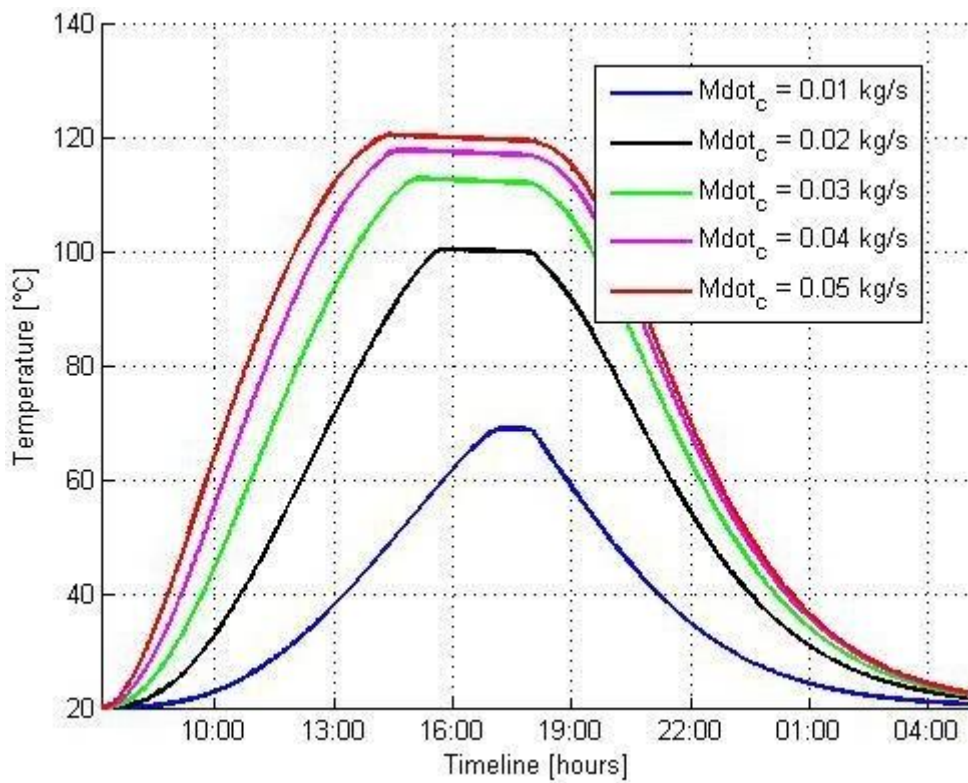


**Figure IV.6:** the evaluation of different  $\dot{m}_c$  on temperature on the middle layer during the day

The middle layer is more sensitive to the charging mass flow rate than the top layer. With

**0.01 kg/s**, the middle layer reaches only about **68–70 °C**. With **0.02 kg/s**, it increases to nearly **100 °C**. For **0.03 kg/s**, the maximum temperature becomes about **112 °C**, while **0.04 kg/s** and **0.05 kg/s** reach approximately **118–120 °C**. This result shows that a higher charging flow rate allows heat to penetrate deeper into the tank and reduces the delay between the upper and middle layers.

**Figure IV.7:** This figure presents the effect of the charging mass flow rate on the bottom layer temperature

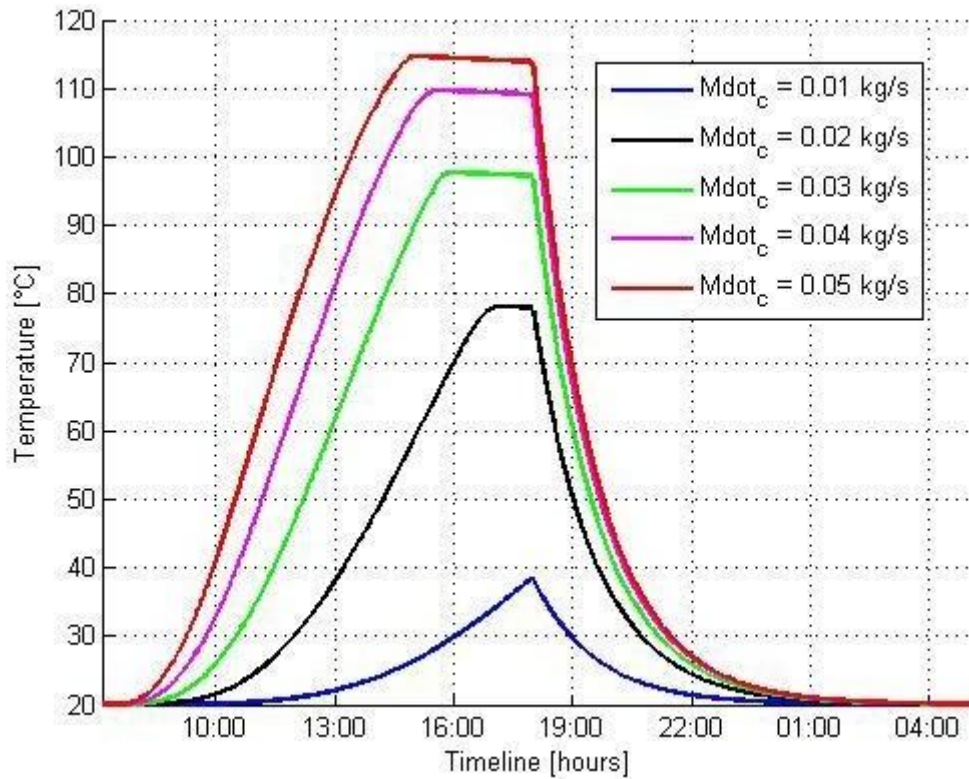


**Figure IV.7:** the evaluation of different  $\dot{m}_c$  on temperature on the bottom layer during the day

The bottom layer shows the clearest effect of the charging mass flow rate. For 0.01 kg/s, the bottom layer reaches only about 38–40 °C, which means that the heat does not reach the lower part effectively. For 0.02 kg/s, the maximum temperature increases to about 78 °C. For 0.03 kg/s, it reaches nearly 98 °C, while 0.04 kg/s and 0.05 kg/s reach about 110 °C and 114–115 °C, respectively. This confirms that higher charging flow rates improve the thermal charging of the whole tank, especially the lower layers.

**Figure IV.8:** This figure shows the effect of different charging mass flow rates on the useful thermal power

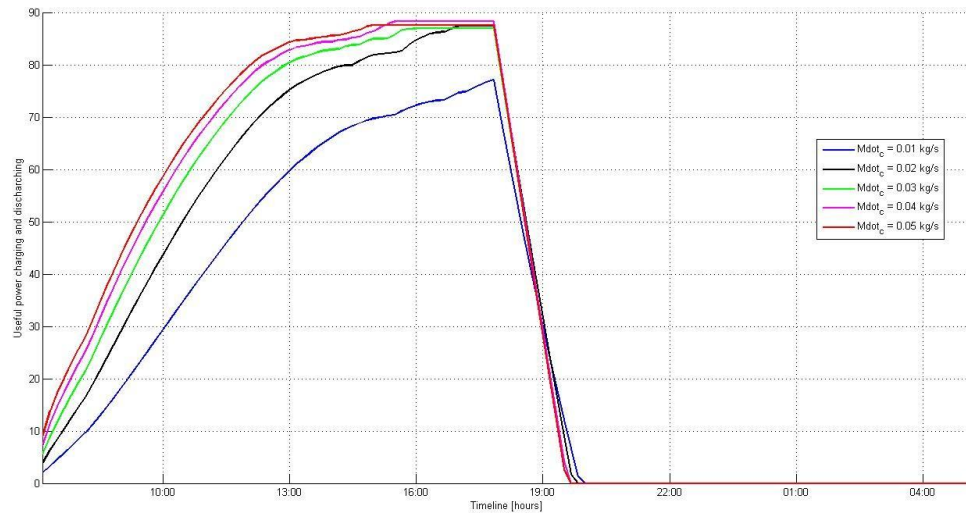


**Figure IV.8:** the evaluation of different  $\dot{m}_c$  on the useful power during the day

The useful charging value increases with the charging mass flow rate. For **0.01 kg/s**, the maximum useful value is about **75**, while for higher flow rates it reaches approximately **85–88**. The curves corresponding to **0.03, 0.04, and 0.05 kg/s** reach high values earlier, around **13:00–15:00**, which means that the tank stores heat faster. After the beginning of discharge, the useful value drops rapidly to zero around **19:00–19:30**. This indicates that increasing charging flow rate improves the stored energy, but the discharge duration remains limited by the load demand.

### 4.3.2 Effect of discharging mass flow rate $\dot{m}_l$

This case studies the influence of the load-side discharging mass flow rate on the tank performance. By changing only the discharging flow rate, the effect on the cooling process, useful discharging power, and duration of heat delivery can be analyzed.

**Figure IV.9:** This figure presents the influence of the discharging mass flow rate on the top layer temperature

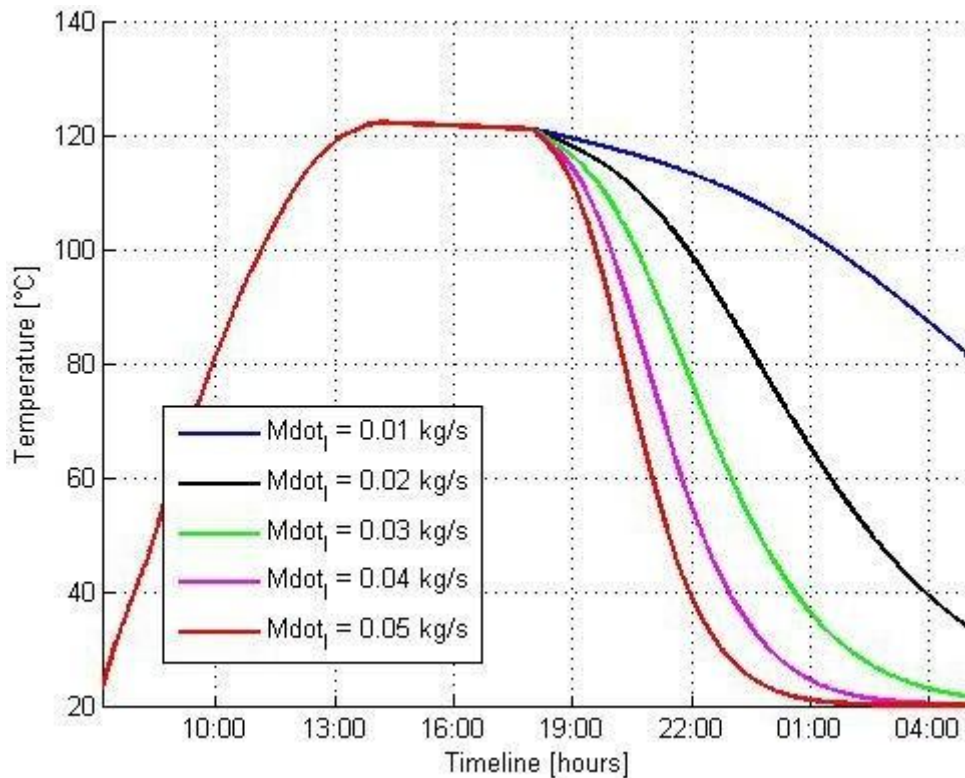


**Figure IV.9:** the evaluation of different  $\dot{m}_l$  on temperature on the top layer during the day

Before discharge, all curves reach almost the same top temperature, about **121–122 °C**, because the charging conditions are identical. After **18:00**, the influence of the discharging mass flow rate becomes clear. With **0.01 kg/s**, the top layer cools slowly and still remains around **80 °C** at **05:00**. With **0.02 kg/s**, it decreases to about **33–35 °C** at the end of the simulation. For higher flow rates, such as **0.04 kg/s** and **0.05 kg/s**, the top layer reaches nearly **20–25 °C** much earlier, around **01:00**. Therefore, increasing the discharging flow rate accelerates the cooling of the tank.

**Figure IV.10:** This figure shows the effect of the discharging mass flow rate on the middle layer temperature

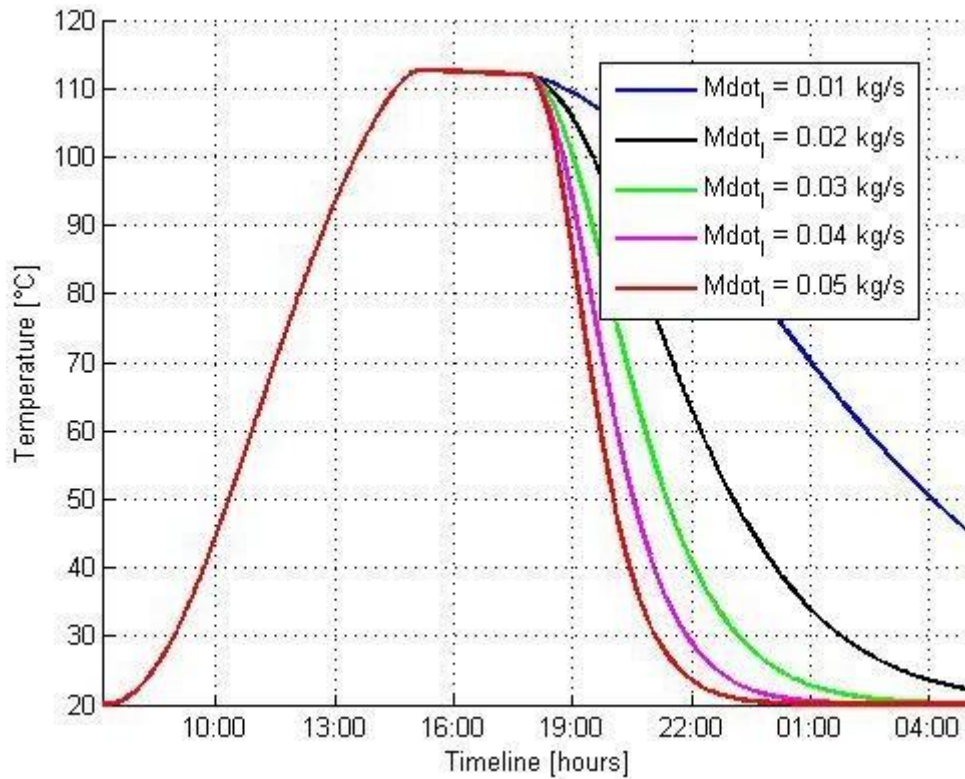


**Figure IV.10:** the evaluation of different  $\dot{m}_l$  on temperature on the middle layer during the day

The middle layer reaches about **112 °C** before discharge for all studied cases. After discharge starts, the cooling rate increases with the discharging mass flow rate. For **0.01 kg/s**, the middle layer still remains around **45 °C** near **05:00**. For **0.02 kg/s**, it decreases to about **23–25 °C** by the end of the simulation. For **0.04 kg/s** and **0.05 kg/s**, the temperature drops close to **20 °C** before or around **23:00–00:00**. This confirms that high load flow rates consume the stored heat much faster.

**Figure IV.11:** This figure presents the influence of the discharging mass flow rate on the bottom layer temperature

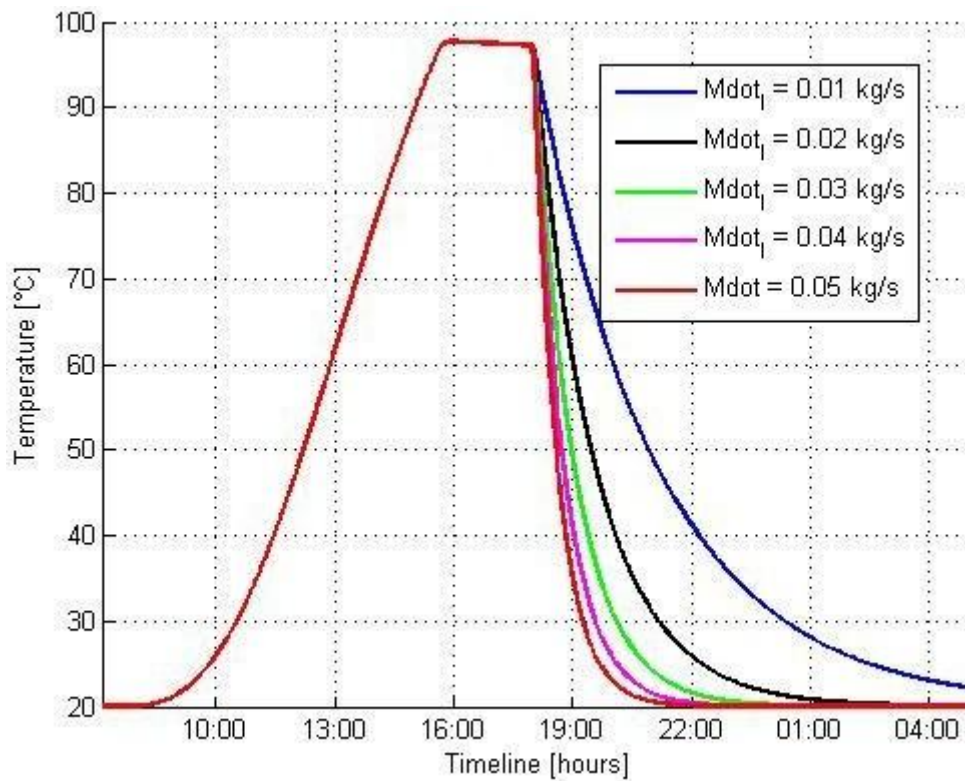


**Figure IV.11:** the evaluation of different  $\dot{m}_l$  on temperature on the bottom layer during the day

The bottom layer reaches a maximum temperature of about 97–98 °C before discharge. Because the return water enters from the bottom, this layer cools very rapidly after 18:00. For 0.05 kg/s, the bottom layer drops to about 20 °C around 21:00. For 0.04 kg/s, it reaches the same value slightly later, around 21:30. For 0.03 kg/s, it approaches 20 °C around 22:00, while for 0.01 kg/s, it cools more slowly and remains around 22–23 °C near 05:00. This shows that the bottom layer is the first zone affected by discharge.

**Figure IV.12:** This figure shows the effect of the discharging mass flow rate on the useful thermal power

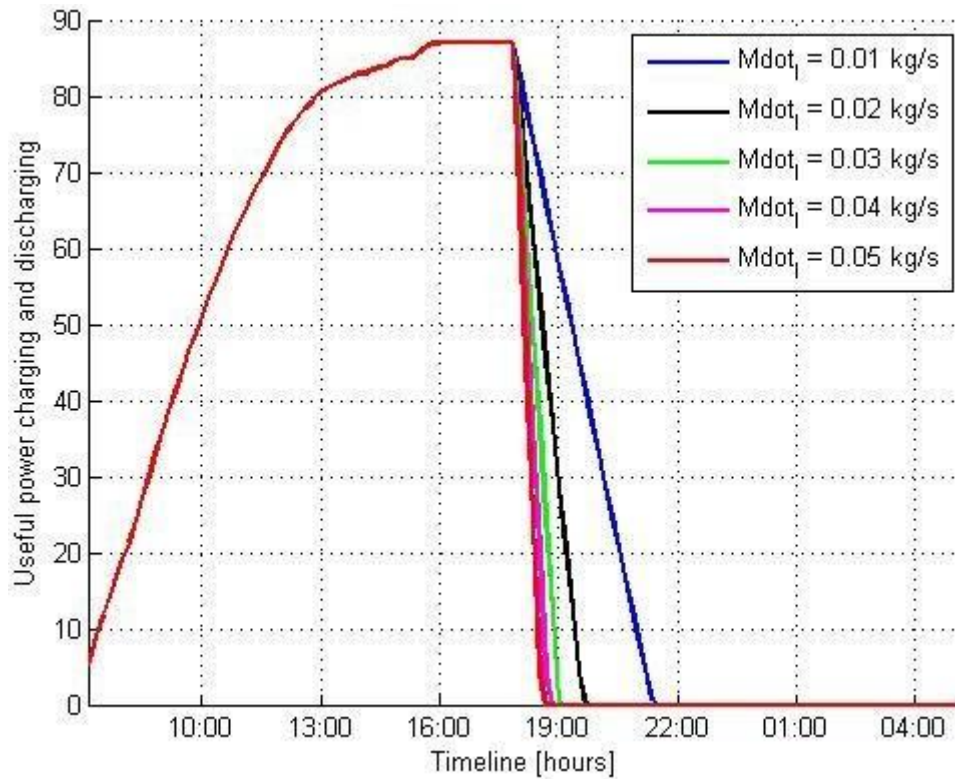


**Figure IV12:** the evaluation of different  $\dot{m}_l$  on the useful power during the day

The useful thermal value reaches about **85–88** before discharge for all cases. However, the time required to consume this stored value changes significantly with the discharging mass flow rate. For **0.05 kg/s**, the useful value drops to zero before **19:00**. For **0.04 kg/s**, it reaches zero around **19:00**, and for **0.03 kg/s**, around **19:10–19:20**. With **0.02 kg/s**, the useful value lasts until about **19:30–20:00**, while with **0.01 kg/s**, it remains available until nearly **21:30**. This proves that lower discharging flow rates increase the duration of heat delivery.

### 4.3.3 Effect of tank capacity V

The purpose of this case is to examine the effect of the storage tank capacity on its thermal response. The tank volume is varied by changing the tank radius while keeping the other operating conditions unchanged ( $\pi, r, H$ ). This allows the influence of storage capacity on temperature evolution and accumulated energy to be evaluated.

$$V_T = \pi \times r^2 \times H$$

**Figure IV.13:** This figure illustrates the effect of tank capacity on the temperature of the top layer

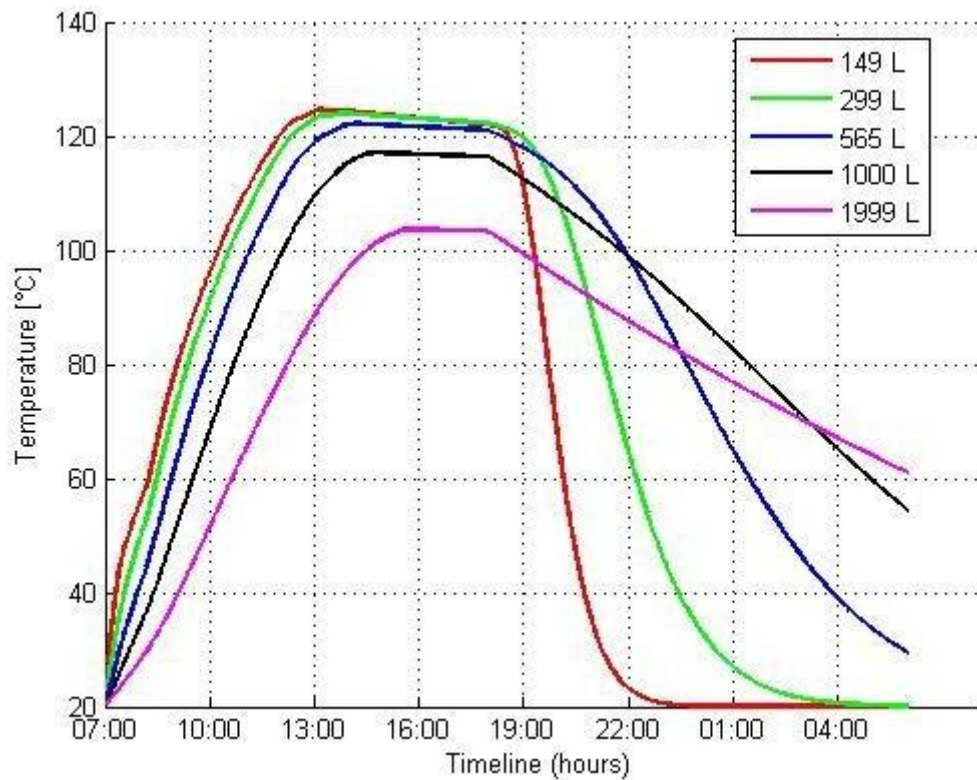


**Figure IV.13:** the evaluation of different V on temperature on the top layer during the day

The top layer temperature is strongly affected by the tank capacity. The smallest tank, **149 L**, heats quickly and reaches about **125 °C** around **13:00**, but it also cools very rapidly after discharge and reaches nearly **20 °C** around **22:00**. The **299 L** tank also reaches about **123–124 °C**, but it keeps heat for a longer time. The **565 L** tank reaches around **122 °C**, while the **1000 L** tank reaches about **117 °C**. The largest tank, **1999 L**, reaches only about **103 °C**, but it cools

more slowly and remains around **60 °C** near **05:00**. This means that small tanks heat faster, while large tanks store heat for longer.

**Figure IV.14:** This figure shows the effect of tank capacity on the middle layer temperature

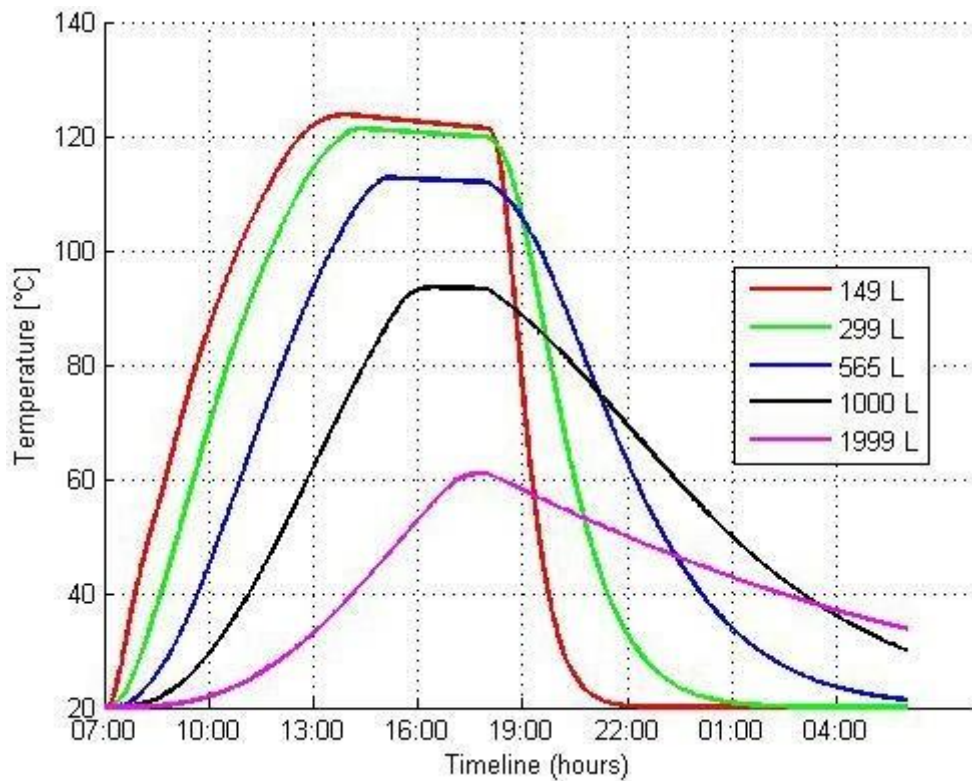


**Figure IV.14:** the evaluation of different V on temperature on the middle layer during the day

For the middle layer, the **149 L** and **299 L** tanks reach high temperatures of about **122–124 °C** and **120–121 °C**, respectively. The **565 L** tank reaches about **112 °C**, while the **1000 L** tank reaches only about **93–95 °C**. The largest tank, **1999 L**, reaches a much lower maximum value of about **60 °C**. This shows that increasing the tank volume increases the thermal inertia, which slows down the heating process, especially in the internal layers.

**Figure IV.15:** This figure presents the effect of tank capacity on the bottom layer temperature

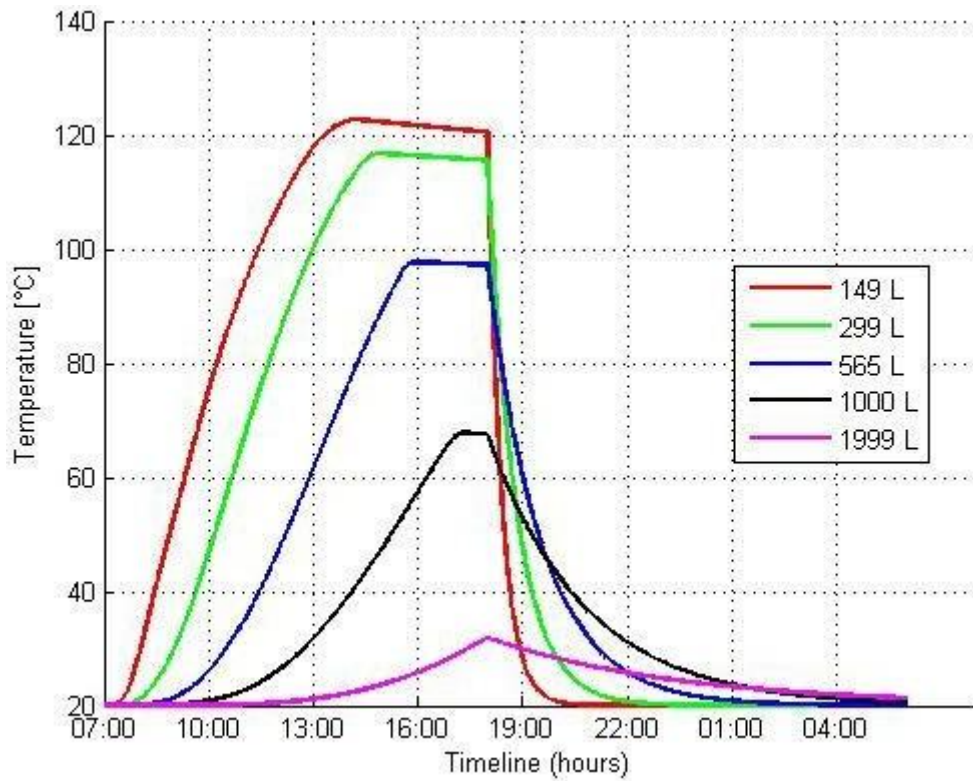


**Figure IV.15:** the evaluation of different V on temperature on the bottom layer during the day

The bottom layer clearly shows the influence of storage volume. For the smallest tank, **149 L**, the bottom layer reaches about **122–123 °C**. For **299 L**, it reaches about **116–117 °C**, and for **565 L**, it reaches approximately **98 °C**. However, for **1000 L**, the maximum temperature is only about **68 °C**, and for **1999 L**, it is around **32 °C**. This indicates that in large tanks, the supplied heat is not sufficient to heat the entire volume uniformly during the same charging period.

**Figure IV.16:** This figure shows the influence of tank capacity on the useful thermal power

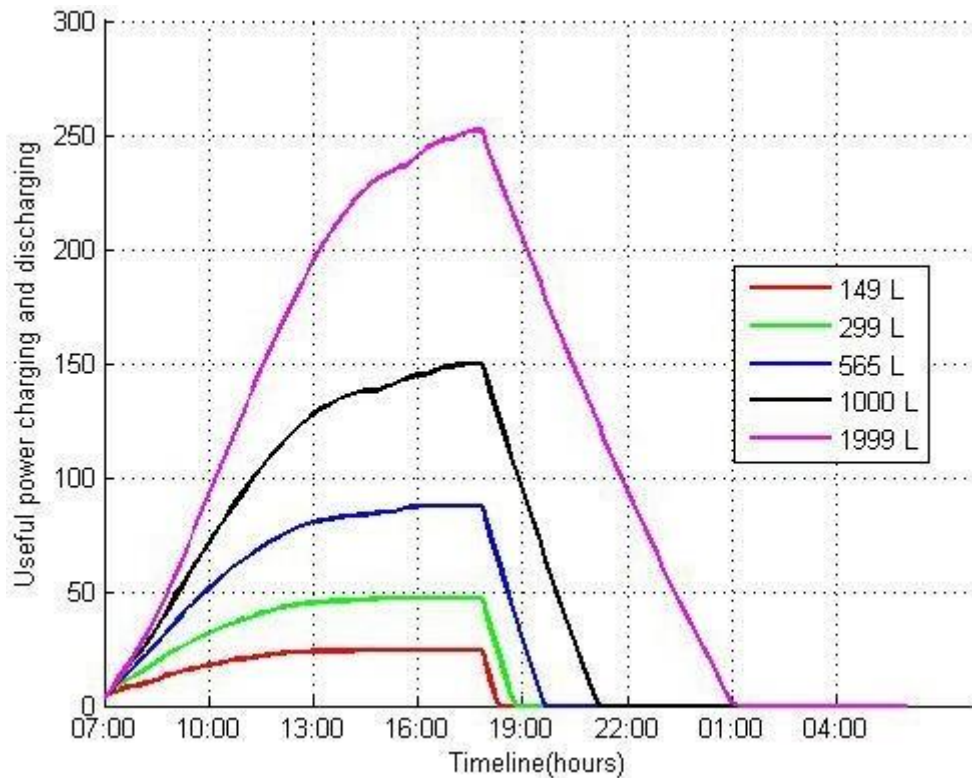


**Figure IV.16:** the evaluation of different V on the useful power during the day

The useful stored value increases strongly with tank capacity. For **149 L**, the maximum useful value is only about **25**, and it becomes zero around **18:30**. For **299 L**, it reaches about **48** and drops to zero around **19:00**. For **565 L**, it reaches nearly **88** and remains available until about **20:00**. For **1000 L**, the useful value reaches around **150** and lasts until about **22:00**. The largest tank, **1999 L**, reaches the highest value, about **250–255**, and remains useful until nearly **01:00**. This confirms that larger tanks store more thermal energy and provide longer discharge duration.

#### 4.3.4 Effect of the Overall Heat Loss Coefficient $U$

In this case, the heat loss coefficient is varied to evaluate its influence on the thermal performances of the storage tank. A lower value of represents better insulation, while a higher value indicates greater heat losses to the ambient environment.

**Figure IV.17:** This figure presents the effect of the overall heat loss coefficient on the top layer temperature

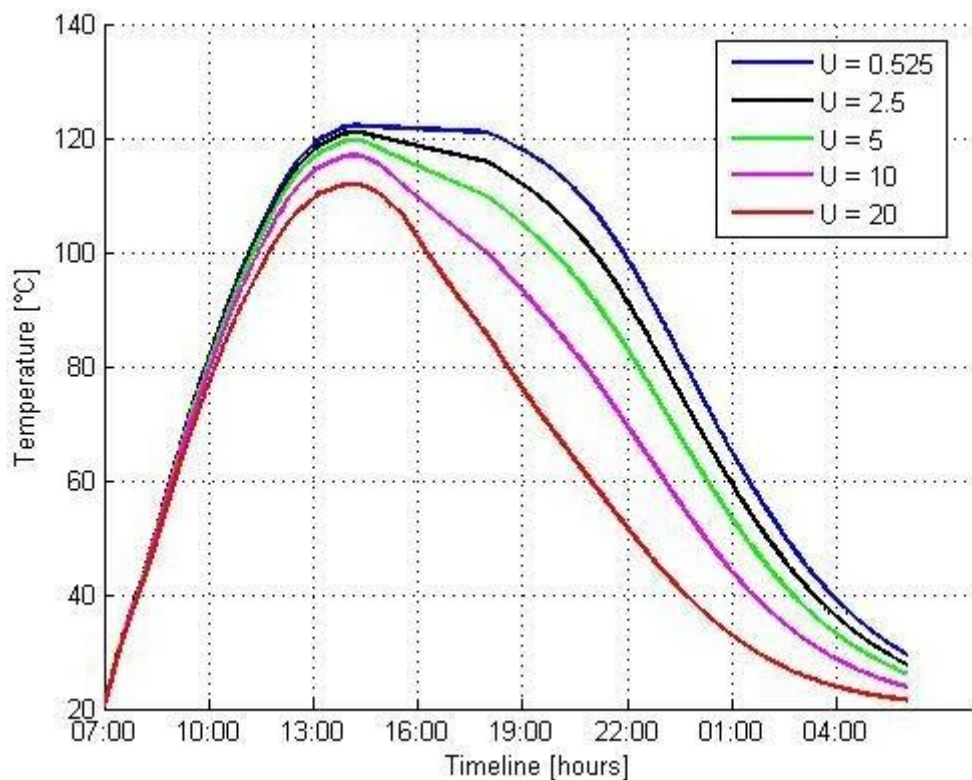


**Figure IV.17:** the evaluation of different  $U$  on temperature on the top layer during the day

The heat loss coefficient has a direct effect on the top layer temperature. With the lowest value,  $U = 0.525$ , the top layer reaches about  $122\text{ }^{\circ}\text{C}$  and remains hotter for a longer period. When  $U = 2.5$ , the maximum temperature is slightly lower, around  $120\text{--}121\text{ }^{\circ}\text{C}$ . For  $U = 5$ , it reaches about  $118\text{--}120\text{ }^{\circ}\text{C}$ , while for  $U = 10$ , the maximum temperature decreases to about  $116\text{ }^{\circ}\text{C}$ . With the highest heat loss coefficient,  $U = 20$ , the maximum temperature is only about  $111\text{--}112\text{ }^{\circ}\text{C}$ . Around  $22:00$ , the top layer is still close to  $95\text{ }^{\circ}\text{C}$  for  $U = 0.525$ , but only around  $55\text{ }^{\circ}\text{C}$  for

$U = 20$ . This shows that higher heat losses reduce both the maximum temperature and the heat retention time.

**Figure IV.18:** This figure shows the effect of the overall heat loss coefficient on the middle layer temperature

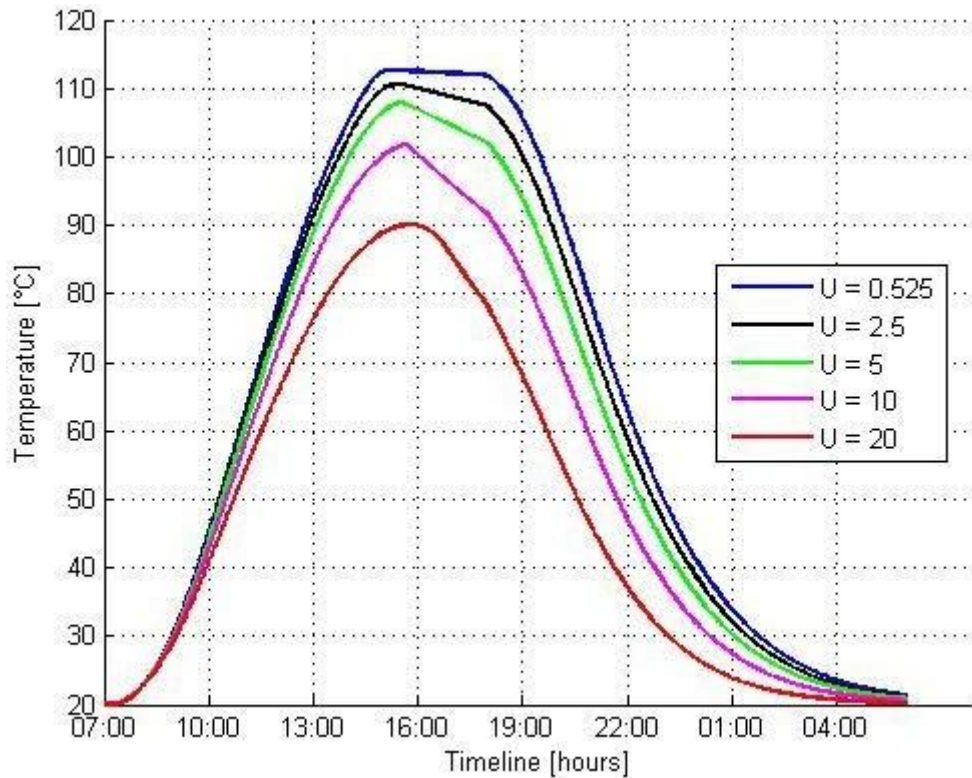


**Figure IV.18:** the evaluation of different  $U$  on temperature on the middle during the day

The middle layer also decreases when the heat loss coefficient increases. For  $U = 0.525$  and  $U = 2.5$ , the middle layer reaches about  $110\text{--}112\text{ }^{\circ}\text{C}$ . For  $U = 5$ , it reaches around  $108\text{ }^{\circ}\text{C}$ , while for  $U = 10$ , the maximum temperature is about  $101\text{ }^{\circ}\text{C}$ . With  $U = 20$ , the middle layer reaches only about  $90\text{ }^{\circ}\text{C}$ . After discharge, all curves decrease toward  $20\text{ }^{\circ}\text{C}$ , but the high-loss case cools faster. This confirms that better insulation helps preserve the thermal energy inside the tank.

**Figure IV.19:** This figure presents the influence of the overall heat loss coefficient on the bottom layer temperature

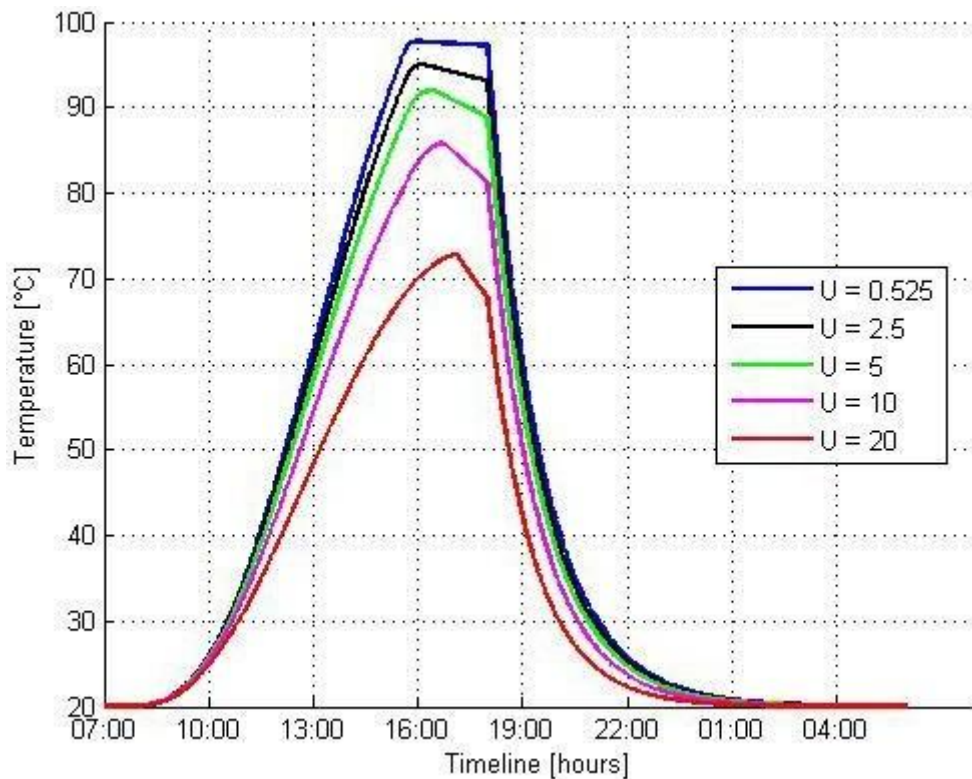


**Figure IV.19:** the evaluation of different  $U$  on temperature on the bottom layer during the day

The bottom layer is also affected by heat losses. With  $U = 0.525$ , the bottom layer reaches about  $98\text{ }^{\circ}\text{C}$ . For  $U = 2.5$ , it reaches about  $95\text{ }^{\circ}\text{C}$ , and for  $U = 5$ , about  $92\text{ }^{\circ}\text{C}$ . When  $U = 10$ , the maximum temperature decreases to about  $85\text{ }^{\circ}\text{C}$ , while for  $U = 20$ , it reaches only about  $72\text{--}73\text{ }^{\circ}\text{C}$ . All cases return close to  $20\text{ }^{\circ}\text{C}$  after discharge, but higher values of  $U$  lead to faster cooling. This means that poor insulation reduces the temperature of the lower part of the tank and decreases the amount of stored heat.

**Figure IV.20:** This figure shows the effect of the overall heat loss coefficient on the useful thermal power

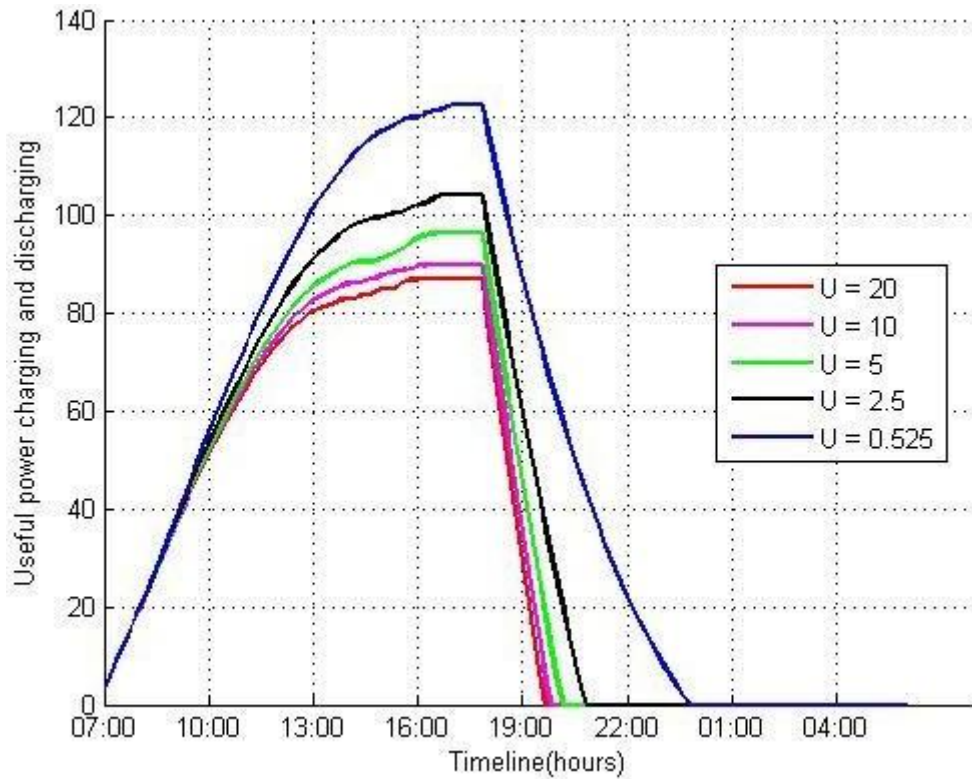


**Figure IV.20:** the evaluation of different  $U$  on the useful power during the day

The useful thermal value decreases when the heat loss coefficient increases. For the best insulation case,  $U = 0.525$ , the useful value reaches the highest level, around **120–122**, and remains available until nearly **00:00**. For  $U = 2.5$ , the maximum value is about **104**, and the useful value becomes zero around **21:30–22:00**. For  $U = 5$ , the maximum value is about **96**, while for  $U = 10$  and  $U = 20$ , it decreases to about **90** and **87**, respectively. The useful value for  $U = 20$  reaches zero earlier, around **19:30–20:00**. This proves that increasing heat losses reduces the stored useful energy and shortens the discharge duration.

## 4.4 Conclusion

In this chapter, the thermal behavior of the stratified hot-water storage tank was analyzed using the developed MATLAB simulation model. The base-case results showed that the tank was successfully charged during the daytime. At the beginning, all layers were close to **20 °C**, while the collector temperature increased progressively until it reached about **125 °C**. During charging, the upper layer heated faster than the lower layers, which confirmed the presence of thermal stratification. At the end of the charging period, the tank reached high temperatures, with Layer 1 around **123 °C** and Layer 5 around **115 °C**, showing that the tank was almost fully charged.

During the discharging period, the results showed that the bottom layer cooled first because of the cold return water entering the lower part of the tank. Layer 5 decreased rapidly toward **20–25 °C**, while the top layer remained hot for a longer time. This behaviour confirms that thermal stratification is useful because it allows the upper part of the tank to continue supplying hot water even when the lower layers have already cooled down.

The parametric study showed that increasing the **charging mass flow rate** improves the heating of the tank, especially in the middle and bottom layers. However, after a certain value, around **0.03 kg/s**, the improvement becomes limited. The study of the **discharging mass flow rate** showed that higher flow rates consume the stored heat faster and reduce the discharge duration. On the other hand, lower discharging flow rates allow the tank to provide useful heat for a longer period.

The effect of **tank capacity** showed that small tanks heat faster but discharge quickly, while larger tanks heat more slowly but store more thermal energy and provide a longer discharge time. Finally, the effect of the **heat loss coefficient** confirmed that good insulation is very important. A low value of **U** allows the tank to keep higher temperatures for a longer time, while high heat losses reduce the stored energy and accelerate cooling.

Overall, the simulation results confirm the importance of thermal stratification, suitable mass flow rates, adequate tank capacity, and good insulation in improving the performance of the thermal storage system. These results provide a useful basis for selecting the best operating parameters and improving the efficiency of stratified hot-water storage tanks.

## **Générale conclusion**

This work focused on the numerical study of a laminated hot water tank associated with a flat plate solar collector. The main objective was to analyze the thermal behavior of the storage tank during the different operating modes, namely charging, discharging and standby, and to evaluate the influence of several operating parameters on the preservation of thermal stratification and system performance. The literature review has shown that thermal energy storage plays an essential role in solar thermal systems because it reduces the mismatch between the availability of solar energy and thermal demand. Among the different storage technologies, the laminated storage tank was selected because it allows the hot water to remain in the upper part of the tank while the colder water remains at the bottom. This thermal separation improves the efficiency of the solar collector and increases the useful availability of the stored thermal energy. The studied system consists mainly of a flat-plate solar collector, a vertical laminated storage tank, a circulation pump and control components. The flat-plate collector absorbs solar radiation and transfers it to the working fluid, while the laminated tank stores the collected heat in different temperature layers. The principle of operation of the system is based on three modes: charging when solar energy is available, discharging when hot water is required by the load and standby when there is no energy input or output. A one-dimensional mathematical model with several nodes has been developed based on the energy balance applied to each reservoir layer. The reservoir was divided into five horizontal layers and the transient temperature evolution was calculated using the explicit Euler numerical method implemented in MATLAB. The model included heat input from the collector, heat extraction by the load, intercalary thermal transport and heat losses in the ambient environment. This approach made it possible to predict the distribution of the temperature inside the tank and to evaluate the useful charging and discharging powers. The simulation results confirmed the ability of the model to reproduce the phenomenon of thermal stratification. During the charging period, the upper layers warmed up faster than the lower ones, which shows that the hot water remained mainly in the upper part of the tank. The temperature of the collector gradually increased and reached about 125 °C, while the layers of the reservoir reached high temperatures at the end of charging. This indicates that the tank has actually been charged under the selected operating conditions. During the discharge period, the lower layers first cooled down due to the cold return water entering the bottom of the tank, while the upper layer remained warm for a longer

time. This result confirms the importance of thermal stratification, as it allows the tank to continue to supply useful hot water even when the lower part is already cooled. The parametric study also showed that the charge mass flow rate, the discharge mass flow rate, the tank capacity and the heat loss coefficient strongly affect the thermal performance of the system. The increase in the mass flow rate of charge improved the heating of the tank, especially in the middle and lower layers, but the improvement became limited after a certain value. The increase in the discharge mass flow accelerated the cooling process and reduced the duration of heat availability. The study of tank capacity showed that small tanks heat up quickly but lose useful energy faster, while larger tanks store more energy and offer longer discharge periods. In addition, the effect of the heat loss coefficient has demonstrated that good insulation is essential to reduce thermal losses and maintain high storage temperatures for longer durations. Overall, this study confirms that laminated thermal storage tanks are effective solutions to improve the performance of solar thermal systems. The preservation of thermal stratification, the correct selection of mass flow rates, the appropriate sizing of the tank and the reduction of heat losses are key factors to improve the efficiency of the system. The MATLAB model developed represents a useful and practical tool to predict the thermal behavior of laminated storage tanks and to support the design and optimization of solar water heating systems.

As future work, the model can be improved by using a larger number of layers, taking into account the variable thermophysical properties, including more detailed heat transfer mechanisms, and validating the numerical results with experimental measurements. Further studies can also investigate advanced storage materials such as phase-change materials and improved input diffuser designs in order to increase storage efficiency and extend the useful operating period of the system.

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