Ministry of Higher Education
and Scientific Research
University of Diyala
College of Engineering

Simulation and Experimental Validation of Melting and Solidification Processes of Double Coils Latent Heat Storage Unit Using CFD

A Thesis Submitted to the Council of College of Engineering, University of Diyala, in a Partial Fulfillment of the Requirements for the Degree of Master of Science in Chemical Engineering

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1447 A.H IRAQ 2026 A.D

Abstract

Phase change materials (PCMs) are widely used for thermal energy storage because of their ability to absorb and release a large amount of heat during the melting and solidification processes. However, these processes usually occur slowly, which reduces the overall efficiency of thermal energy storage systems. In addition, only a limited number of studies have investigated the behavior of PCMs in double helical coil heat exchangers.

The aim of this study is to enhance the melting and solidification processes of PCMs and reduce the time required for these phase transitions. For this purpose, a double helical coil heat exchanger with different geometrical configurations was used. Paraffin wax was selected as the PCM, while water was used as the heat transfer fluid in a latent heat thermal energy storage (LHTS) system. Both experimental and numerical investigations were carried out. In the experimental work, water at 90 °C was used during the melting process, while water at 30 °C was used during the solidification process. The initial temperature of the PCM during the melting process was 30℃ (room temperature) in both experimental and simulation studies, and 90℃ during the solidification process. Several temperature sensors were placed at different radial and axial positions to measure the temperature of the paraffin wax. The experimental work focused on studying the melting process in the double helical coil heat exchanger. In the simulation work enhancements were achieved by modifying the coil pitches (the distance between the coil turns) in three configurations, while fins were added in one configuration. Five configurations were investigated. The first configuration was the normal double helical

coil heat exchanger, which served as the base case and was referred to as NDHC. In the second configuration, both coils were compacted downward and referred to as BCCD. In the third configuration, the inner coil was compacted downward and referred to as ICCD. In the fourth configuration, the outer coil was compacted downward and referred to as OCCD. The fifth configuration consisted of the normal double helical coil heat exchanger with added fins and was referred to as FDHC. The same boundary conditions were applied in both the numerical and experimental studies. Also that, studied the mesh selection and the time step to achieve the accuracy and computational cost, the mesh size was used 800000, 3000000,6800000 cells with time step 0.1sec and The results demonstrated that the mesh with 3,000,000 cells offered a good compromise between accuracy and computational cost. Three time steps were considered (0.1, 0.2 and 0.5 s), which were used for each of the five cases of double helical coil design and a computational mesh with around 3,000,000 elements. Results of 0.2 s time step were very similar with those of 0.1 s and no differences in temperature profiles or phase change behavior were observed. The numerical model was validated by comparing the melting results of the NDHC configuration with the experimental results. The numerical results showed good agreement with the experimental data. The ICCD and OCCD configurations showed higher melting rates compared with the NDHC configuration, achieving about a 35% reduction in melting time. The melting time was 95 minutes for ICCD and 105 minutes for OCCD, compared with 150 minutes for NDHC. The BCCD configuration also enhanced the melting process, with a melting time of 105 minutes. The melting time in the FDHC configuration was 120 minutes. In general, the melting time ranged between 90 and 150 minutes depending on the configuration.

The solidification process was slower than the melting process. The FDHC configuration showed noticeable improvement in the solidification process, reducing the solidification time by about 27.3% compared with NDHC. The solidification time was 120 minutes for FDHC and 165 minutes for NDHC. In the configurations with reduced coil pitches, the solidification time was longer than the base case, reaching 290 minutes for ICCD and 425 minutes for OCCD. In the BCCD configuration, the solidification process stopped because the upper half of the PCM did not solidify for a long time. The main parameters studied during the melting and solidification processes were the liquid fraction, velocity distribution, heat flux, temperature distribution, and the outlet temperature of the water.

Chapter One

Introduction

1.1. Overview

In a recent year, there is a significant importance for sustainable energy storage, because of the growing need for energy in every aspect of daily and the associated problems with fossil fuels, such as high cost, causes climate change, air pollution because of combustion of fossil fuel, global warming, environment damage caused by fossil fuel extraction, and combustion. Renewable energy, derived from natural sources like solar, wind, water, plants and animals, presents a promising solution to these challenges.

However, renewable energy is often intermittent and may not be available in all time or in all locations. To address this issue, energy storage technologies have been developed. Those technologies can be categorized into: (i) Mechanical energy. (ii) thermal energy storage. (iii) electrochemical energy storage. (iiii) Hydrogen-based storage. (iiiii) electrical energy storage (Enasel et al. ,2025)

1.2. Thermal energy storage

The energy is stored by heating or cooling energy in a storage system, this energy can be stored for a long time until it is needed for cooling and heating application and power generation (Zalba et al.,2003). Thermal energy storage classification: thermal and thermochemical, thermal classified into latent and sensible. Sensible thermal energy storage occurs by changing the temperature while the phase still constant. While the change of phase with constant temperature then occurs the latent thermal energy storage. Latent heat is associated with phase transitions, such as: solid to liquid (melting)-solid to solid (polymorphic transitions): the changes happen in the molecular arrangement, and the solid to vapor (sublimation). Thermochemical classified into heat pump, heat of reaction, and thermochemical pipe line. Figure (1.1) showed the types of thermal storage (Gasia et al.,2017) . Thermal energy storage by heat pump means the system uses the heat pump to generate cooling and heating after that stores the heat in the materials such as water or ice (Zhou et al.,2026). Heat of reaction is the storing and the releasing of the thermal energy achieved during chemical reactions(André et al.,2016). Thermochemical pipe line is a system used to store and transport thermal energy for long distances (Reay,2015).

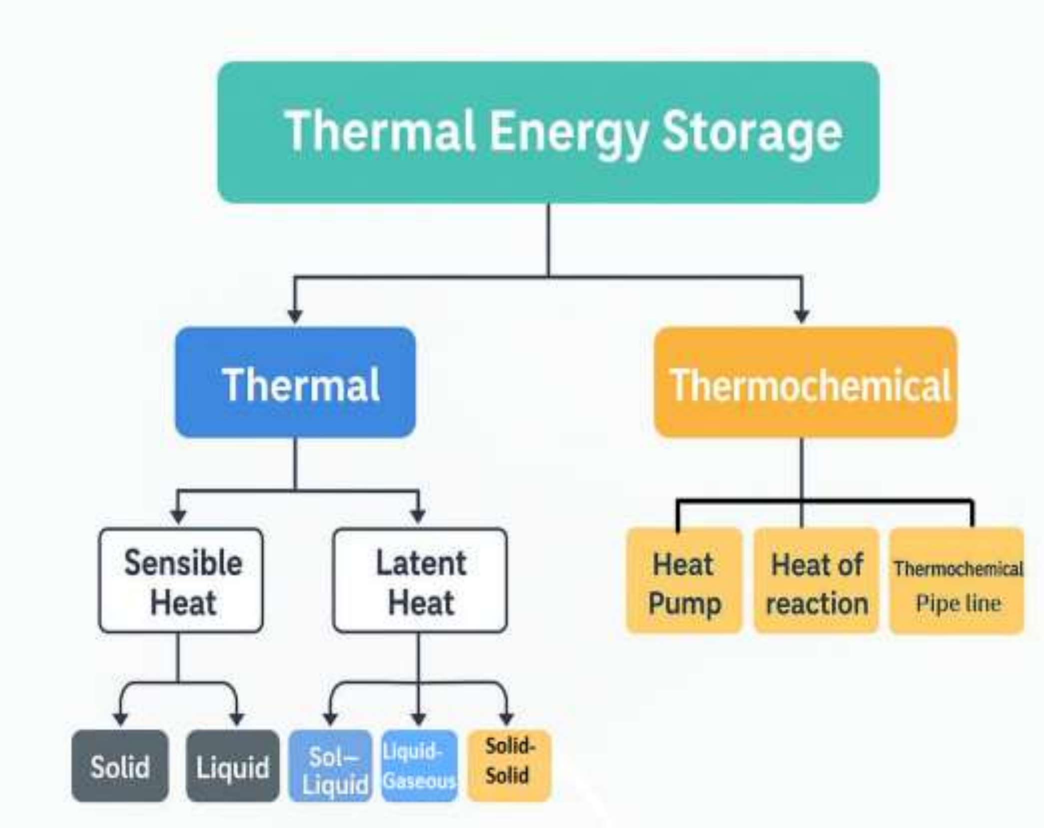

Fig. (1.1) Types of thermal storage.

1.3 Phase change materials (PCMs)

Due to their ability in store (charge) and release (discharge), the PCM have attention of researches. When the PCM absorbs heat and transitions from a solid to liquid this, process called charging (melting). While when the PCM release heat from, liquid to the solid this a process called discharging (solidification). Inside the PCM, the thermal energy stored by two ways the first is the latent heat and the second is the sensible heat. Researchers investigated in PCM, heat exchanger and thermal conductors, to enhance the performance of the storage capacity and energy release. These achieved by the comprehension of the melting performance of the PCMs in various geometrical configurations, including rectangular, cylindrical, spherical and heat exchanger (Tabassum, 2009). Figure 1.2 illustrates the relationship between temperature and thermal energy during the melting process of a phase change material (PCM).

In simple terms:

1. Solid (Sensible heating):

When the PCM is heated from temperature $T_1$to T_s, the material remains solid, and its temperature increases linearly. The added energy only raises the temperature without changing the phase this is known as sensible heat (Farid et al.,2004)

2. Melting (Latent heating):

Between T_s and T_L, the PCM starts to melt. During this stage, the temperature remains almost constant even though heat is continuously added. This energy is used to break molecular bonds and convert the solid into liquid. This phase is known as latent heat (Sharma et al.,2009)

3. Liquid (Sensible heating)

After the entire material has melted (beyond T_L), further heating increases the temperature of the liquid phase. Again, this is a sensible heating process (Cabeza et al., 2011).

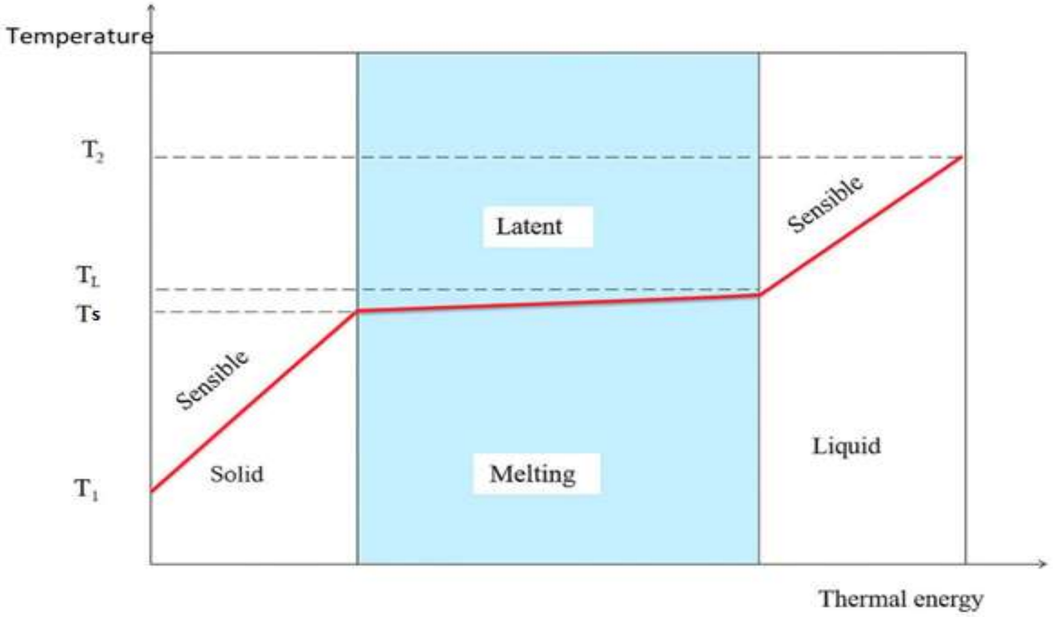

Fig.(1.2) PCM melting process diagram (Al-Dokhan,2019)

During the melting process such as shown in Figure 1.3, the stored energy gradually increases as the PCM absorbs heat, increasing rapidly in the phase change region where latent heat is stored. During the solidification process such as shown in Figure 1.4, the stored energy continuously reduces as the material releases heat, with the steepest drop occurring in the phase change zone. The overall curves show the typical sensible and latent heat behavior of PCM during heating and cooling (Sharma et al.,2009).

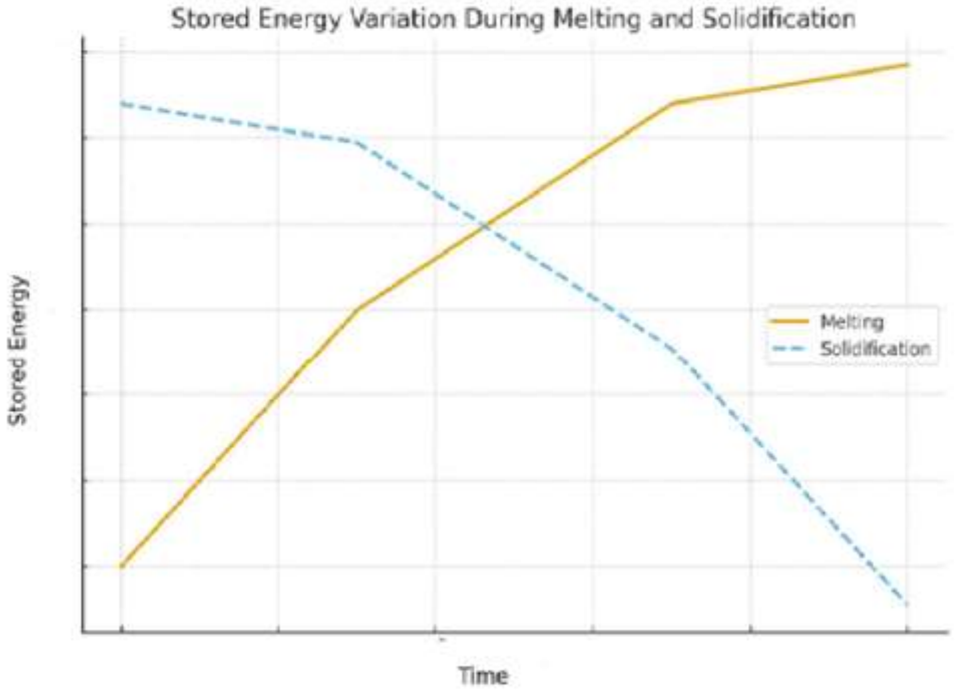

Fig. (1.3) Stored energy variation during melting and solidification processes (Sharma et al.,2009)

1.3.1 Phase change material classification

The classification of the PCMs:

1. Organic materials (paraffin compounds and non-paraffin compounds).
2. Inorganic materials (salt hydrate and metallic).
3. eutectics materials (organic-organic, inorganic-inorganic, inorganic-organic).

The phase change materials have variation in properties including the melting point, the coefficient of volumetric expansion, latent heat value, and thermal energy storage capacity(Gasia et al.,2017).

1.3.2 Phase change materials properties.

The properties of the PCMs classified into two groups:

1. Thermal and physical characteristics:

-Elevated efficiency to storage energy with low volume variation.

-Low thermal conductivity.

-The temperature during the phase change of the PCMs stay constant.

-It is built to be long lifespan (Gasia et al.,2017 and Gao et al.,2013).

2. Chemical properties:

- Eco-friendly.
- Safe, stable, and corrosion resistance.
- Non-reactive.

1.3.3 Application of PCM

Phase Change Materials (PCMs) have gained significant attention in recent years because of their capacity to absorb and discharge substantial thermal energy during phase change processes (Zalba et al.,2003). They are widely used in applications such as:

- Thermal energy storage
- Heat removal from electronics in spacecraft and astronaut garments.
- Medical devices.
- Insulation of buildings.
- Cooling of battery.
- Electronic cooling.
- Clothing industry for firefighters.

1.3.4 Melting and solidification of the PCM

Phase Change Materials (PCMs) are materials that can store and release heat by changing their phase, usually from solid to liquid or liquid to solid, at nearly constant temperatures. This makes them useful for storing thermal energy(Zalba et al.,2003).

1.3.4.1 Melting process

as the temperature of a phase change material (PCM) reaches its melting point, it starts to absorb thermal energy without a significant rise in temperature. This energy, referred to as the latent heat of fusion, is consumed in breaking the molecular bonds within the solid phase, converting it into a liquid. During this phase transition:

- The PCM’s temperature stays almost constant.
- The absorbed heat is stored as latent heat.
- The melting process generally initiates at the interface in contact with the heat source and progressively advances in ward (Sharma et al.(2009).

1.3.4.2 Solidification Process

When the ambient temperature falls below the PCM’s freezing point, the material begins to solidify by releasing the latent heat it previously stored during melting. Throughout this transformation:

- Heat is released from the PCM to the surrounding environment.
- Its temperature remains fairly steady until the solidification process concludes.
- Typically, solidification starts at the cooler external boundaries and moves towards the center (Cabeza et al.,2011).

1.4 Heat exchanger

A heat exchanger is a device designed to transfer thermal energy between two or more fluids at different temperatures without allowing them to mix (Cengel and Ghajar). There are several main types of heat exchanger and can be classified as follows (Incropera et al.,2018):

1. Shell and tube heat exchanger
2. Plate heat exchanger
3. Double pipe heat exchanger
4. Fin tube heat exchanger
5. Helical coil heat exchanger

However, in addition to the above types of heat exchanger, there are more types available that depend on the application and process requirements.

1.4.1. Helical coil heat exchanger

Helical coil heat exchanger is a type of heat exchanger consisting of a tube wound into a helical shape, placed inside a shell . A fluid flows through the coil, while another fluid is contained within the surrounding vessel. The helical design offers a larger heat transfer surface area and requires less space due to its compact shape. Figure (1.5) shows the shell and heat exchanger. Additionally, the helical configuration enhances heat transfer efficiency compared to straight tubes, as it generates secondary flow patterns (swirling flows) that improve the overall heat exchange between the two fluids (Naphad et al.,2018).

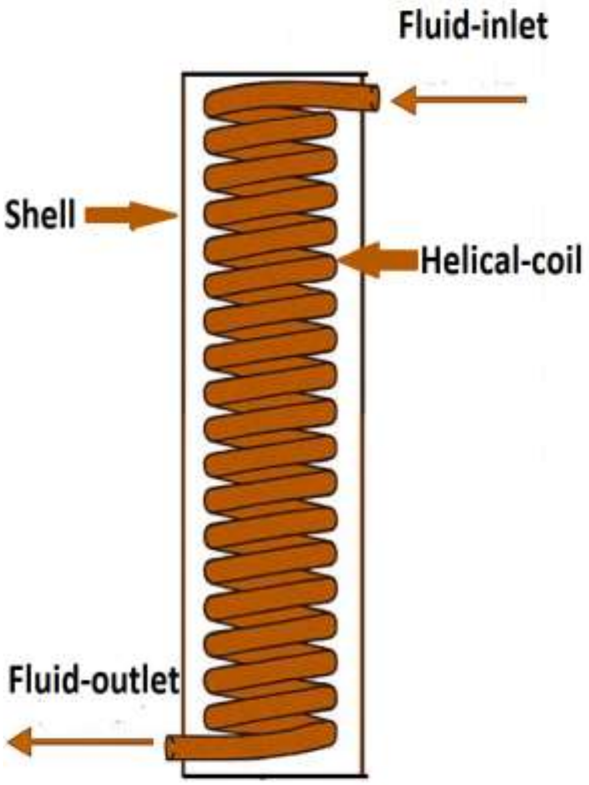

Fig.(1.4) Shell and helical coil heat exchanger.

1.4.2. Types of helical coil heat exchanger

There are several types of helical heat exchanger. The main types are shown below (Naphon et al.,2006)

1. Single helical coil heat exchanger.

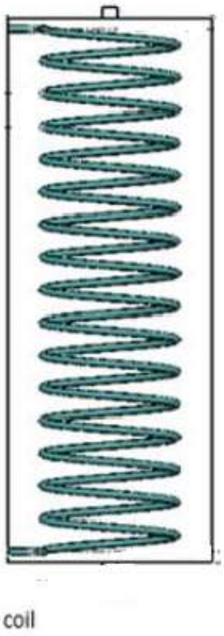

Fig. (1.5) Schematic diagram of the single coil (Ali et al., 2021)

2. Double helical coil heat exchanger.

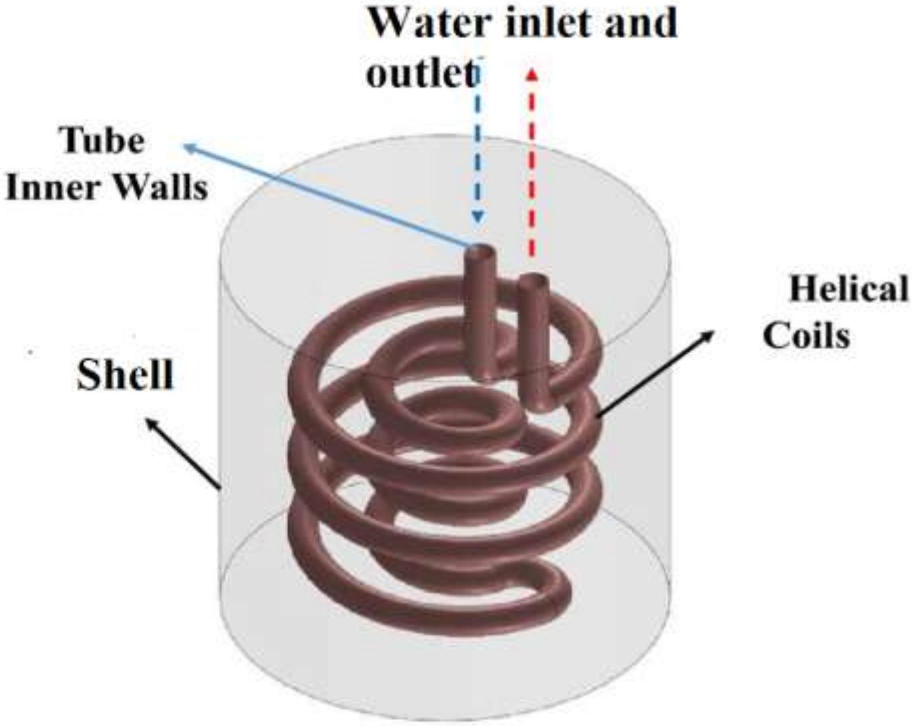

Fig. (1.6) Schematic diagram of the double helical coil (Afsharpanah et al.,2019).

3. Multi helical coil heat exchanger.

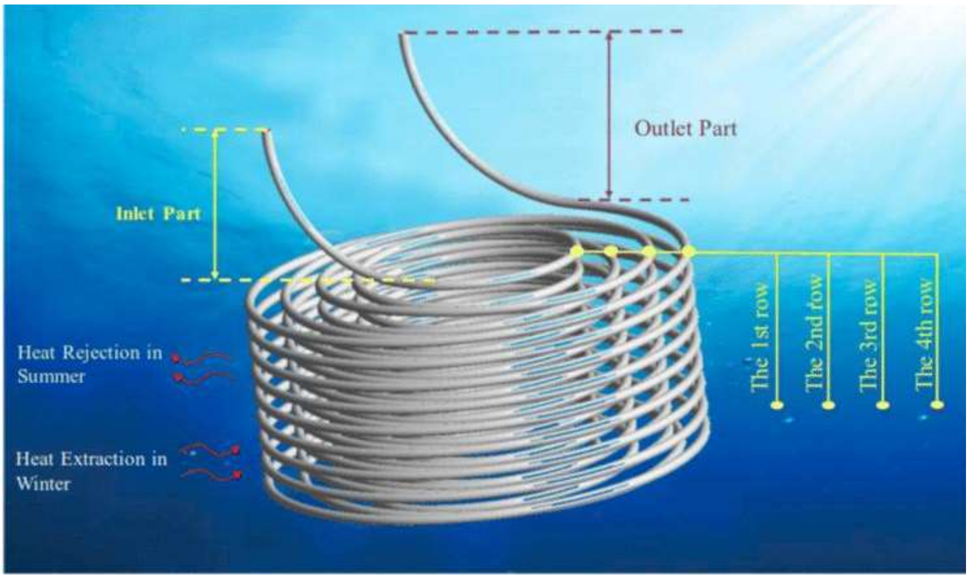

Fig. (1.7) multi helical coil heat exchanger (Rashidi et al., (2021).

4. Vertical helical coil heat exchanger.

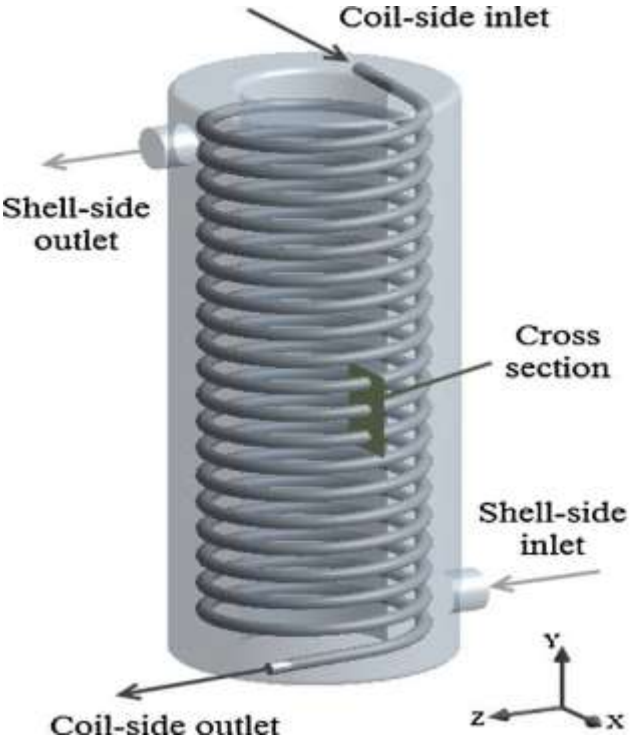

Fig.(1.8) Vertical helical coil heat exchanger(Bahrehmand et al., 2016).

5. Horizontal helical coil heat exchanger.

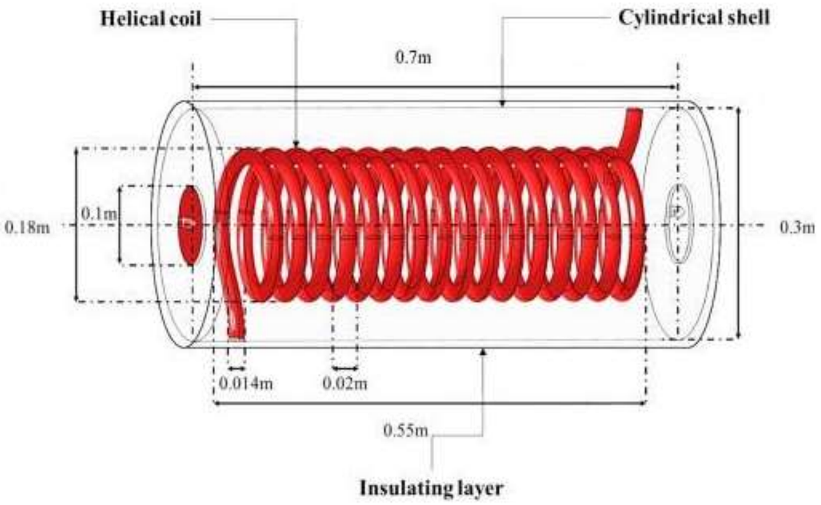

Fig.(1. 9) Schematic diagram for the horizontal helical coil heat exchanger (Agrebi et al.,2025).

6. Conical coil heat exchanger.

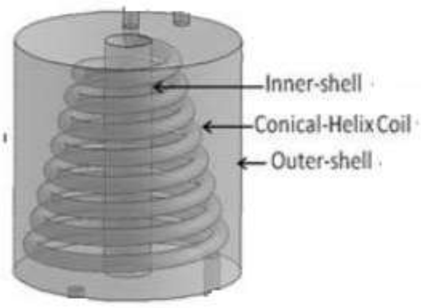

Fig.(1.10) schematic diagram for the conical coil heat exchanger (Mehtre et al., 2022).

7. Spiral plate heat exchanger.

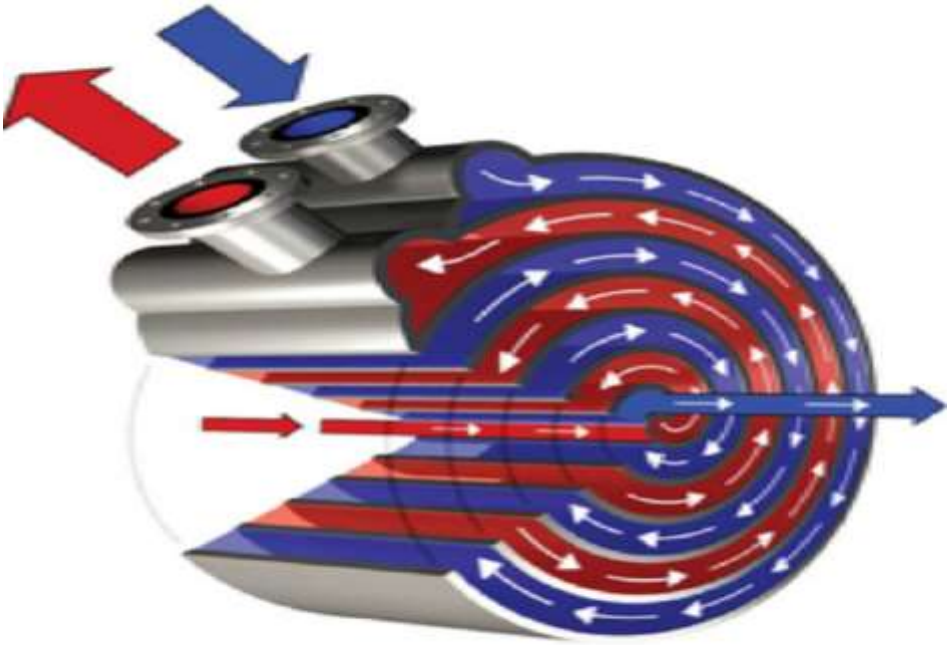

Fig.(1.11) Schematic diagram for the spiral plate heat exchanger (Sabharwall et al., 2007).

1.4.3 Advantage of helical coil heat exchanger

There are several advantages of helical coil heat exchanger (Shaik et al.,2020, Brose et al.,2018,and Al Mukit et al.,2023), such as:

1. Its use enhances heat transfer
2. It can be employed in applications with limited space.
3. Due to its compact shape, its needs less material for fabrication.
4. Inside the tube it enhances the turbulence flow.

1.4.4. Disadvantage of helical coil heat exchanger

Just as the helical coil heat exchanger has advantages, it also has disadvantages (Shaik et al.,2020, Brose et al.,2018,and Al Mukit et al.,2023), such as:

1. Numerical analysis is difficult.

2. Its cost is higher than other types.
3. It is difficult to clean from the inside.

1.5. Problem Statement

Although phase change materials (PCMs) offer significant advantages for thermal energy storage systems due to their high latent heat capacity, their low thermal conductivity remains a major limitation, leading to slow melting and solidification rates. Various heat exchanger designs have been proposed to improve heat transfer performance in PCM-based systems, with helical and spiral coil configurations demonstrating promising results. However, the thermal behavior of PCMs within double helical coil heat exchangers, especially under different coil configurations, has not been comprehensively studied. Additionally, the accuracy of numerical simulations requires reliable experimental validation to ensure their applicability in practical systems. Therefore, there is a need for a systematic investigation of the effect of different double helical coil configurations on the thermal performance of PCMs, alongside experimental verification of the numerical results.

1.6The aim of the study

This work aims to enhancing the thermal performance of the PCM during the melting and solidification processes in a helical coil heat exchanger using statistical investigation over different coil configurations. Moreover, by experimentally examining the regular layout, this study focuses on confirm the computational predictions and decrease melting and solidification times.

1.7 Objectives

1. To develop five different configurations and to simulate them numerically Analysis of a double helical coil heat exchanger using CFD methodology.

2. To analyze the influence of coil configuration on the thermal performance of PCM in terms of liquid fraction, energy stored and released, velocity distribution, melting time, solidification time, and temperature dispersion.

3. excite a laboratory scale of helical coil which controlled the melting and solidification processes.

4. compare and verify the numerical simulation results with experimental measurements.

5. determine the best coil configuration in order to improve energy consumption (melting and solidification times) with recommendations on thermal energy storage system application

6. investigate the behavior of dimensionless numbers as Nusselt (Nu), Rayleigh (Ra) and Stefan (St) which would help understanding deeper on both heat transfer and phase change phenomenon in this system.

1.8 Research layout

The structure of this thesis extends through six chapters. Chapter One: background, aims and method overview of the use of PCMs for thermal energy storage and the application of double helical coils to enhance heat transfer pagination. Chapter Two is a comprehensive literature review of existing experimental and numerical research on PCM melting and solidification with specific regards to issues surrounding coil pitch separation distance and the placement of fins. Experimental setup, material, instruments and procedures to systematically study the thermal performance of the PCM system are presented in Chapter Three. Chapter 4 describes the numerical modeling and simulation in ANSYS Fluent, including the governing equations and boundary conditions as well as the validation with experimental evidence. Chapter 5 summarizes the findings of both experimental and numerical investigation, concentrating on liquid fraction, temperature distribution, stored energy and melting rate of growth as well as comparing different coil types. Last but not least, Chapter Six gives a summary of the conclusions and suggests future work and potential applications.

الخلاصة:

تُستخدم مواد تغيّر الطور (PCMs) على نطاق واسع في أنظمة خزن الطاقة الحرارية نظرًا لقدرتها العالية على امتصاص وإطلاق كميات كبيرة من الحرارة أثناء عمليتي الذوبان والتصلب. ومع ذلك، فإن هذه العمليات عادة ما تكون بطيئة، مما يقلل من كفاءة النظام بشكل عام. كما أن الدراسات التي تناولت سلوك مواد تغيّر الطور داخل المبادلات الحرارية ذات الملف الحلزوني المزدوج ما زالت محدودة.

تهدف هذه الدراسة إلى تحسين أداء الذوبان والتصلب لمواد تغيّر الطور وتقليل الزمن اللازم لكلتا العمليتين، وذلك باستخدام مبادل حراري مزدوج الحلزون بعدة تصاميم هندسية مختلفة. تم اختيار شمع البرافين كمادة تغيّر الطور، واستخدم الماء كسائل ناقل للحرارة ضمن منظومة خزن حراري كاملة تعتمد على الحرارة الكامنة (LHTS). تضمّنت الدراسة جزأين : تجريبية وعددية. في الجزء التجريبي، استُخدم ماء بدرجة حرارة 90 °م أثناء عملية الانصهار. كما تم تثبيت عدة مجسات حرارية في مواقع شعاعية ومحورية مختلفة لقياس درجة حرارة شمع البارافين. ركّزت التجارب العملية على دراسة عملية الانصهار داخل المبادل الحراري ذي الملف الحلزوني المزدوج الاعتيادي.

أما في الجزء العددي، فقد تم تحسين الأداء من خلال تغيير المسافة بين لفات الملف الحلزوني (coil pitch)مع إضافة زعانف حرارية في أحد التصاميم. وبذلك تم اختبار خمسة نماذج مختلفة، حيث كان النموذج الأول هو المبادل الحلزوني المزدوج الاعتيادي وتم اعتماده كحالة أساسية ورُمز له(NDHC) في النموذج الثاني تم تقليل المسافة بين لفات الملفين باتجاه الأسفل ورُمز له (BCCD).في النموذج الثالث تم تقليل المسافة بين لفات الملف الداخلي فقط ورُمز له (ICCD).في النموذج الرابع تم تقليل المسافة بين لفات الملف الخارجي فقط ورُمز له (OCCD). أما النموذج الخامس فكان المبادل الاعتيادي مع إضافة زعانف حرارية ورُمز له (FDHC).تم تطبيق نفس شروط الحدود في كل من الدراسة العددية والتجريبية.

كما تم إجراء دراسة لاختيار حجم الشبكة العددية والخطوة الزمنية المناسبة لتحقيق التوازن بين الدقة والكلفة الحسابية، حيث استُخدمت شبكات بعدد خلايا 800000 و3000000 و6800000 خلية، مع خطوة زمنية مقدارها 0.1 ثانية. وأظهرت النتائج أن الشبكة ذات 3,000,000 خلية تحقق أفضل توازن بين الدقة وزمن الحساب. كذلك تم اختبار ثلاث خطوات زمنية (0.1 و0.2 و0.5 ثانية)، وأظهرت النتائج أن الخطوة الزمنية 0.2 ثانية تعطي نتائج متقاربة جدًا مع 0.1 ثانية دون اختلاف ملحوظ في توزيع درجة الحرارة أو سلوك التحول الطوري، لذلك تم اعتمادها في الحسابات.

تم التحقق من صحة النموذج العددي من خلال مقارنة نتائج الانصهار في الحالة الأساسية (NDHC)مع النتائج التجريبية، حيث أظهرت المقارنة توافقًا جيدًا بين النتائج العددية والعملية. اما بالنسبة للدراسة العددية أظهرت النتائج أن تصميمي (ICCD) و (OCCD)حققا أعلى معدل انصهار مقارنة بالحالة الأساسية، حيث انخفض زمن الانصهار بحوالي 35%، إذ بلغ زمن الانصهار 95 دقيقة في حالة ICCD و105 دقائق في حالةOCCD ، مقارنة بـ150 دقيقة في الحالة الأساسية. كما حسّن تصميم (BCCD) عملية الانصهار أيضًا بزمن بلغ 105 دقائق، في

حين كان زمن الانصهار في حالة (FDHC) حوالي 120 دقيقة. وبشكل عام تراوح زمن الانصهار بين 90 و150 دقيقة حسب نوع التصميم.

أما عملية التصلب، فقد كانت أبطأ من عملية الانصهار في جميع الحالات. وأظهر تصميم (FDHC)تحسنًا واضحًا في عملية التصلب، حيث انخفض زمن التصلب بنسبة 27.3% مقارنة بالحالة الأساسية، إذ بلغ 125 دقيقة مقابل 165 دقيقة في الحالة الأساسية. في المقابل، أدّت التصاميم ذات تقليل المسافة بين لفات الملف إلى زيادة زمن التصلب، حيث وصل إلى 290 دقيقة في حالة ICCD و425 دقيقة في حالة OCCD. أما في حالة(BCCD) ، فقد توقفت عملية التصلب في الجزء العلوي من المادة متغيرة الطور لفترة طويلة، مما أدى إلى عدم اكتمال التصلب في الزمن المدروس .تمت دراسة عدة متغيرات أساسية خلال عمليتي الانصهار والتصلب، شملت الكسر السائل(Liquid fraction) ، وتوزيع السرعة، والفيض الحراري، وتوزيع درجة الحرارة، ودرجة حرارة خروج الماء، و كذلك الاعداد اللابعدية dimension less numbers

(Nu number, Stefan number, Rayleigh number).

وزارة التعليم العالي والبحث العلمي
جامعة ديالى
كلية الهندسة

محاكاة وتحقق تجريبي لعمليات الانصهار والتجمد لوحدة تخزن حرارة كامنة ثنائية الملفات باستخدام CFD

رسالة مقدمة الى
قسم الهندسة الكيمياوية/ كلية الهندسة / جامعة ديالى /
كجزء من متطلبات الدراسة لنيل درجة الماجستير
في الهندسة الكيمياوية

تقدم بها
اية محمود نصيف

بأشراف

أ.د أنيس عبدالله كاظم

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