Universitat de Lleida

New thermal energy storage systems for building applications

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Universitat de Lleida

DOCTORAL THESIS

New thermal energy storage systems for building applications

Boniface Dominick Mselle

Thesis presented for the Doctorate degree at the University of Lleida

PhD Programme in Engineering and Information Technology

Directors

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Summary

The overwhelming energy consumption, and greenhouse gases emissions due to high world population in recent years require new technologies to reduce the speed of climate change. The buildings sector consumes about 33% of the overall energy and is responsible for 28% of CO_2 emissions [1]. Given the geographic distribution of the world population, cooling energy consumption is foreseen to increase even more in the next decades. For that reason and in line with sustainable development goals, this PhD thesis is framed on developing new high-performance technologies that will facilitate the incorporation of renewable energy sources in buildings. The study is realized through in-depth consultation and conceptualization of the state of the art, accompanied by three experimental investigations on novel evaporator-TES modules directly integrated into a refrigeration system.

The study assessing the state of the art on the topic mapped statistical and conceptual information, helping to identify the trends, new perspectives, and knowledge gaps. The results laid a foundation for the experimental investigations. The second study evaluated the performance of the system in three operating modes and various external conditions. The results reported a limited operating range of the system and a high stratification effect during the charging process at high compressor power. The third study aimed at identifying the potential of the components in the module reported; PCM energy density was more than six times the sensible materials in the module and average charging/discharging power was more than double during the phase change period compared to the entire process. Finally, the last study was carried out to assess the performance of the modules based on different internal configuration designs reporting key performance indicators (KPIs). The results indicated unique potential in each design configuration; each performance indicator was affected independently, the coefficient of performance (COP) and energy storage density are the least affected KPIs while the state of charge at thermal equilibrium is the most affected KPI.

Resumen

El abrumador consumo de energía y las emisiones de gases de efecto invernadero debido a la alta población mundial en los últimos años requieren nuevas tecnologías para reducir la velocidad del cambio climático. El sector de la edificación consume alrededor del 33% de la energía total y es responsable del 28% de las emisiones de CO_2 [1]. Dada la distribución geográfica de la población mundial, se prevé que el consumo de energía para refrigeración aumente aún más en las próximas décadas. Por ello, y en línea con los objetivos de desarrollo sostenible, esta tesis doctoral se enmarca en el desarrollo de nuevas tecnologías de alto rendimiento que faciliten la incorporación de fuentes de energía renovables en los edificios. El estudio se realiza a través de una consulta y conceptualización en profundidad del estado del arte, acompañado de tres investigaciones experimentales sobre nuevos módulos de evaporador-TES integrados directamente en un sistema de refrigeración.

El estudio que evaluó el estado del arte sobre el tema recogió información estadística y conceptual, lo que ayudó a identificar las tendencias, las nuevas perspectivas y las brechas de conocimiento. Los resultados sentaron las bases para las investigaciones experimentales. El segundo estudio evaluó el funcionamiento del sistema en tres modos de operación y varias condiciones externas. Los resultados reportaron un rango operativo limitado del sistema y un alto efecto de estratificación durante el proceso de carga a alta potencia del compresor. El tercer estudio tuvo como objetivo identificar el potencial de los componentes del módulo considerado; la densidad de energía del PCM fue más de seis veces mayor que la de los materiales sensibles en el módulo y la potencia promedio de carga/descarga fue más del doble durante el período de cambio de fase en comparación con todo el proceso. Finalmente, el último estudio se llevó a cabo para evaluar el rendimiento de los módulos para diferentes diseños de la configuración interna mediante indicadores clave de rendimiento (KPI). Los resultados indicaron un potencial único en cada configuración de diseño; cada indicador de rendimiento se vio afectado de forma independiente, el coeficiente de rendimiento (COP) y la densidad de almacenamiento de energía son los KPI menos afectados, mientras que el estado de carga en equilibrio térmico es el KPI más afectado.

Resum

L'aclaparador consum d'energia i les emissions de gasos d'efecte hivernacle a causa de l'elevada població mundial en els darrers anys requereixen noves tecnologies per reduir la velocitat del canvi climàtic. El sector de la edificació consumeix al voltant del 33% de l'energia total i és responsable del 28% de les emissions de CO_2 [1]. Donada la distribució geogràfica de la població mundial, es preveu que el consum d'energia per a refrigeració augmenti encara més en les properes dècades. Per això, i en línia amb els objectius de desenvolupament sostenible, aquesta tesi doctoral s'emmarca en el desenvolupament de noves tecnologies d'alt rendiment que facilitin la incorporació de fonts d'energia renovables als edificis. L'estudi es realitza mitjançant una consulta i conceptualització en profunditat de l'estat de la tècnica, acompanyado de tres investigacions experimentals sobre nous mòduls evaporador-TES integrats directament en un sistema de refrigeració.

L'estudi que avalua l'estat de l'art sobre el tema va recollar la informació estadística i conceptual, ajudant a identificar les tendències, les noves perspectives i els buits de coneixement. Els resultats van establir les bases per a les investigacions experimentals. El segon estudi va avaluar el rendiment del sistema en tres modes de funcionament i diverses condicions externes. Els resultats van reportar un rang de funcionament limitat del sistema i un efecte d'estratificació elevat durant el procés de càrrega a una potència elevada del compressor. El tercer estudi tenia com a objectiu identificar el potencial dels components del mòdul considerat; la densitat d'energia del PCM era més de sis vegades més gran que la dels materials sensibles del mòdul i la potència mitjana de càrrega/descàrrega va ser més del doble durant el període de canvi de fase en comparació amb tot el procés. Finalment, el darrer estudi es va dur a terme per avaluar el rendiment dels mòduls per a diferents dissenys de la configuració interna mitjançant indicadors clau de rendiment (KPI). Els resultats van indicar un potencial únic en cada configuració de disseny; cada indicador de rendiment es va veure afectat de manera independent, el coeficient de rendiment (COP) i la densitat d'emmagatzematge d'energia són els KPI menys afectats, mentre que l'estat de càrrega en equilibri tèrmic és el KPI més afectat.

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Nomenclature

Abbreviation	**Definition**
PCM	Phase change material
TES	Thermal energy storage
SOC	State of charge
HEX	Heat exchanger
COP	Coefficient of performance
HTF	Heat transfer fluid
KPI	Key performance indicator
HP	Heat pump
DHW	Domestic hot water
TES_i	Thermal energy storage module
Cp	Specific heat capacity
E	Energy
$E_{ch,@\mathrm{T}}$	Energy stored until temperature T
Al	Aluminum
Ref	refrigerant
T	Temperature
$\dot{E}_i$	Power
$\bar{\dot{E}}_i$	Average power
eq	Thermal equilibrium
ε	Effectiveness
u	Uncertainty
ΔT	Temperature difference
$\dot{V}$	Volumetric flow rate
P	Pressure
ρ	Density
eva	Evaporator
$cond$	condenser
max	maximum
ch	Charged
$disc$	discharged
a	Ambient
av	Average
h	Enthalpy
k	Thermal conductivity
#	Number of
TP	PCM temperature
IN	Inlet
OUT	Outlet
WMO	World meteorological organization
Ppm	Parts per million

ppb	Parts per billion
RACHP	Refrigeration, air-conditioning, heat pumps
NZEB	Net zero energy buildings
IEA	International energy agency
PV	Photovoltaic

1. Chapter1: Introduction

This chapter highlights the background, the state-of-the-art, the motivation, and the objectives of the PhD thesis.

1.1 Background and Motivation

Climate change, global warming, and greenhouse gas emissions are among the major cross-cutting issues that require immediate action. According to six international datasets consolidated by the World Meteorological Organization (WMO) [2], presented in Figure 1, the last five decades reported the highest temperature increase of all time. The last seven years are reported the warmest on record with 2021 at 1.11 ± 0.13 °C above the pre-industrial era (1850-1900).

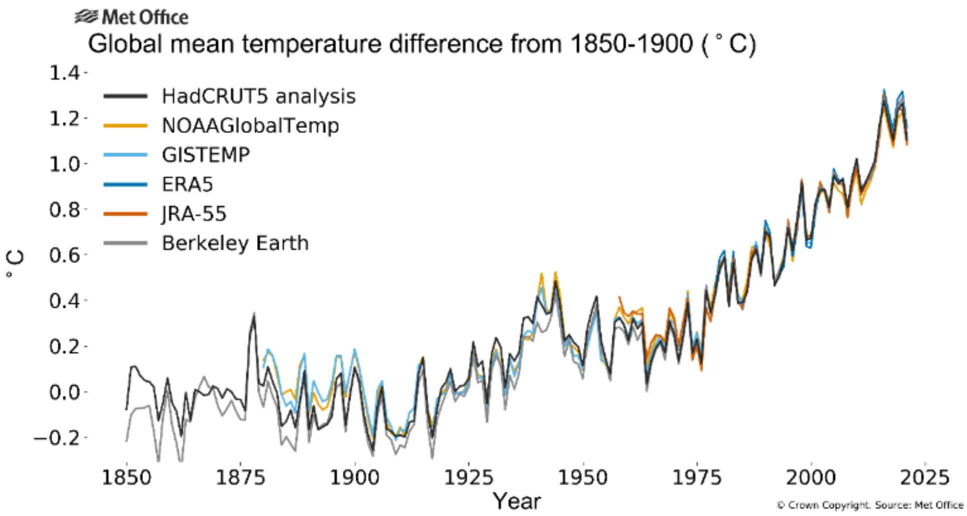
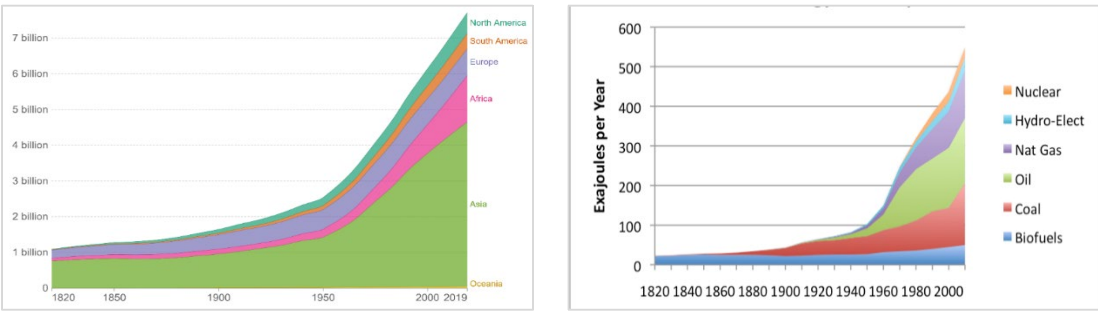


Figure 1. Global temperature increase [2].

The impacts of climate change are evident and are already manifested through various aspects. In [2], the mean sea level rise between 1993 and 2002 was reported 2.1 mm/year while it was more than double between 2013 and 2021, portraying evidence of the accelerated glacial melting due to global warming. According to the *global risks report 2022* in [3], other evidence including outbreaks of droughts, floods, fires, species loss, and scarcity of resources are repeatedly reported and the impacts are foreseen to trigger more insecurities on human health, force millions of people to migrate and others. In the same report, environmental risks such as extreme weather and climate action failure were pointed out as the top risks on a global scale in the short, medium, and long term.

However, one major cause of the increasing global warming is the drastic increase in greenhouse gas emissions that plays a role in trapping the solar heat in the earth´s atmosphere. The levels of greenhouse gas emissions are reported to drastically increase in recent decades compared to the pre-industrial era. The new levels by 2020 were 413.2 parts per million (ppm) of CO_2, 1889 parts per billion (ppb) of methane, and 333.2 ppb of N_2O, marking an increase of 149% of CO_2, 262% of methane, and 123% of N_2O compared to the pre-industrial (1750) levels [2].

The overwhelming increase of world population [4], and the increase of living standards and technology, play a major role in the increase of energy consumption, something that imposes more threats to climate change. The world population tripled in the last 70 years (Figure 2a). The trend of world energy consumption shows a similar relation as the world population growth (Figure 2b), something that shows a great connection between the two. Threats to climate change are more amplified because fossils fuels are the major sources of electricity production [5,6]. Energy demand is foreseen to rise around 1.3% each year until 2040 [7], calling for more sustainable energy systems to combat climate change.



(a) (b)

Figure 2. World trend in (a) population growth [4] and (b) energy consumption [8].

In recent decades, efforts to slow down climate changes through applying sustainable systems gain more support at a small level and global level. Among the major efforts are highlighted in the Kyoto protocol [9], the Paris agreement [5], and the COP26 report [10,11]. These frameworks call for common ground and agency in tackling climate change issues. Here, a commitment to a healthy recovery is invited through supporting the use of renewable energy sources and ensuring access for all. However, although the use of renewable energy sources has increased in recent years, this is overshadowed by the increasing energy demand still maintaining fossils fuels as the major energy sources. In the report provided by IEA [1], in 2018 on energy consumption (Figure 3), renewable energy share accounted for only 11%. Moreover, it was reported that in the last decade, the share of fossil fuels barely changed and was always around 80%.

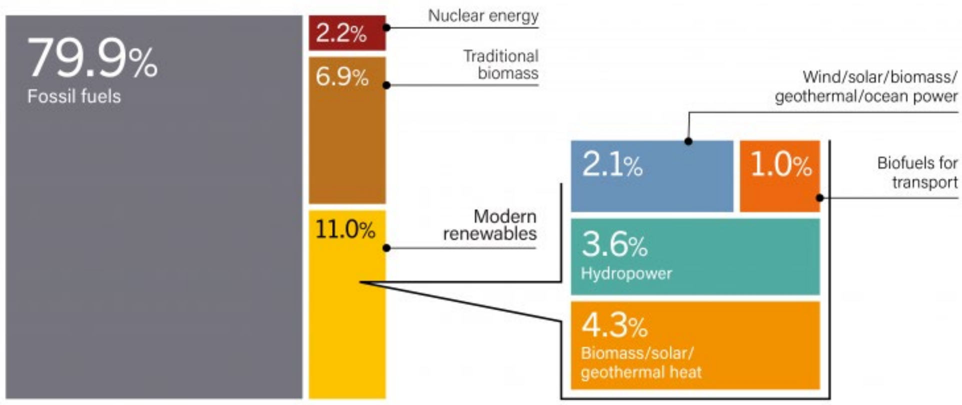


Figure 3. The estimated renewable share of total final energy consumption in 2018 (adapted from IEA data) [1].

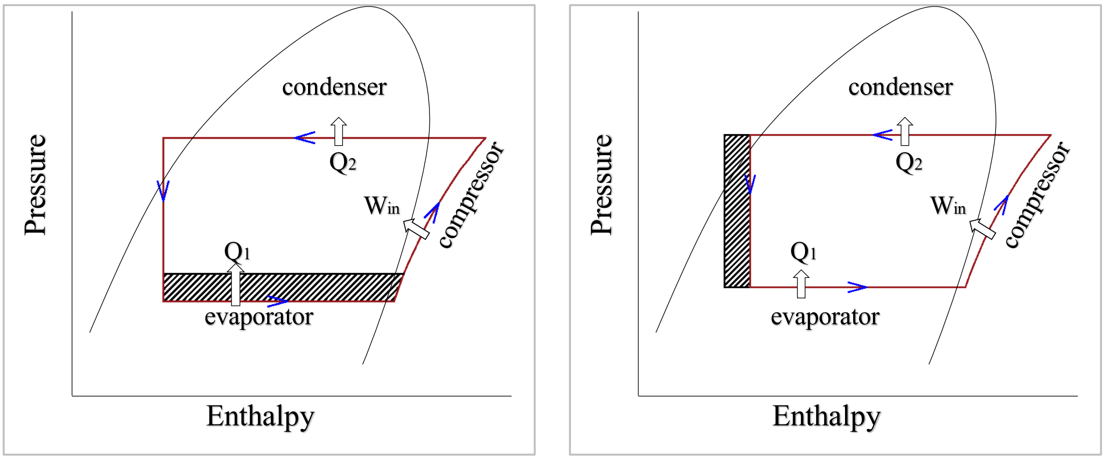
Efficient energy management of building systems has a major role in minimizing the overall energy consumption. The building sector consumes about 33% of the final energy and contributes to about 28% of the global energy-related CO_2 emissions [1]. Around 77% of the energy in the buildings sector is for heating and cooling, i.e. space heating and cooling, domestic hot water (DHW), and cooking. Although in recent years renewable energy systems have attained rapid growth in the buildings sector [7], a great challenge for their use in building applications is based on their intermittent nature, leading to mismatching conditions between the demand side and the production side. In response to that, thermal energy storage (TES) systems offer a promising solution to smoothen the fluctuations/peaks in either the demand or the production side due to their capability to store the extra energy for future consumption.

TES technologies can be classified into three types, i.e. sensible energy storage, latent energy storage, and thermochemical energy storage [12]. Sensible energy storage is undergone by increasing or decreasing the temperature of the storage material, while in latent energy storage, energy is stored at nearly constant temperature by taking advantage of phase transition of the phase change materials (PCMs) [13]. Thermochemical energy storage is based on the use of the heat of reaction in a reversible physical or chemical process/reaction.

1.2 Latent TES integration in building active energy systems

Refrigeration, air-conditioning, and heat pumps (RACHP) systems are the main devices used to cover heating and cooling demands in buildings. The refrigeration systems are used mainly to maintain the temperature of products at low temperature, the air-conditioning systems are used for regulating the temperature and humidity of an ambient to provide the best comfort conditions (mainly for space cooling), while heat pumps are used mainly for space heating. These systems contain integrated control mechanisms to work according to the user set conditions, taking part as active systems according to Net Zero Energy Buildings (NZEB). These systems are widely used in domestic applications and large commercial and industrial applications. Until 2018, RACHP systems consumed between 25% and 30% of the global electricity [1]. According to the International Energy Agency (IEA), the number of refrigerators is forecasted to double while that of air-conditioners to increase from 1.5 to 5.5 billion units between 2015 and 2050. More than half of the projected energy demand growth by 2050 on space cooling is attributed to emerging economies (China, India, and Indonesia). Moreover, cooling is reported to become the strongest driver of growth in buildings' electricity demand, responsible for 40% of the total growth.

Given the expected increase in energy demand for cooling, two prudent measures to slow down climate change include increasing renewable energy share and improving the performance of the systems. The use of TES systems coupled with renewable energy sources is reported to provide the latter double benefits, i.e. increasing the performance of the systems and increasing the renewable energy share. Theoretically, one way of improving the performance of a refrigeration cycle is achieved by reducing the compression ratio, which means reducing the compressor work (W_{in}), or increasing the sub-cooling degree at the condenser which results to increased cooling capacity ($\dot{Q}_1$) at the same compressor power, as demonstrated in Figure 4, which can be achieved using PCM.



(a) (b)

Figure 4. Pressure-enthalpy diagram of a refrigeration cycle with performance improvement by (a) reduced compression ratio (b) increased sub-cooling degree.

1.3 Paper 1: Trends and future perspectives on the integration of phase change material in heat exchangers

1.3.1 Overview

Phase change materials (PCM) are potential candidates for latent energy storage in various applications due to their high energy storage [14]. The technologies used for their implementation play a huge role in the energy storage density and the ability to charge/discharge energy. In practical application, the common three energy storage types are: (i) a storage type where the heat transfer fluid (HTF) is also the storage medium, e.g. slurry (a mixture of HTF and encapsulated PCM) [15], (ii) a storage type with heat transfer on the surface on TES system, e.g. facade with PCM [16], and (iii) a storage type with heat transfer on the internal surfaces, e.g. heat exchanger type [17]. However, the heat exchanger storage type is applied in a wide range of applications since it is equipped with characteristics that enhance the heat transfer process given the low thermal conductivity of PCM [13].

Finally, a huge volume of studies on the topic, bibliometric and keywords analyses were carried out to assess the state-of-the-art and identify the trends, the new perspectives, and the knowledge gaps.

1.3.2 Contribution to the state-of-the-art

The holistic evaluation of the bibliometric data was carried out revealing an overview and a benchmark for the heat exchanger latent TES type. Unlike traditional review papers, this study combined quantitative (statistical) analysis and qualitative analysis highlighting a broader perspective on the topic. The objectives and scope of the study were:

(I) To identify the trends and patterns of the state-of-the-art.

(II) To identify the major contributions based on authors, affiliations, geographical distributions, journals, subject area, and publication type.

(III) To identify the literature gaps and new emerging perspectives.

The methodology applied is highlighted in Figure 5. Two query strings shown in Table 1, relevant to the topic, were used to retrieve data from Scopus database on 26 April 2020, sampled and analysed through bibliometric and keywords methods. Here, VOSviewer software [18] was used to sample and present the occurrence and connection between keywords mapping key aspects on the topic. The major contributions in Query 1 were revealed and the literature gaps were further studied in Query 2. Since the main objective of Query 2 was to exhaustively study the literature gaps identified in Query 1, a review of the relevant subtopics was included. Finally, a discussion of the two queries was carried out providing a further understanding of the topic.

Table 1. Implementation of PCM (a) in a HEX, Query 1, and (b) at the evaporator, Query 2

Query 1	TITLE-ABS-KEY ((PCM OR "phase chang* material*" OR "latent energy storag*" OR "latent heat Storag*") AND "heat exchanger")
Query 2	TITLE-ABS-KEY ((((PCM OR "phase chang* material*" OR "latent energy storag*" OR "latent heat storag*") AND "heat exchanger")) AND evaporator*)

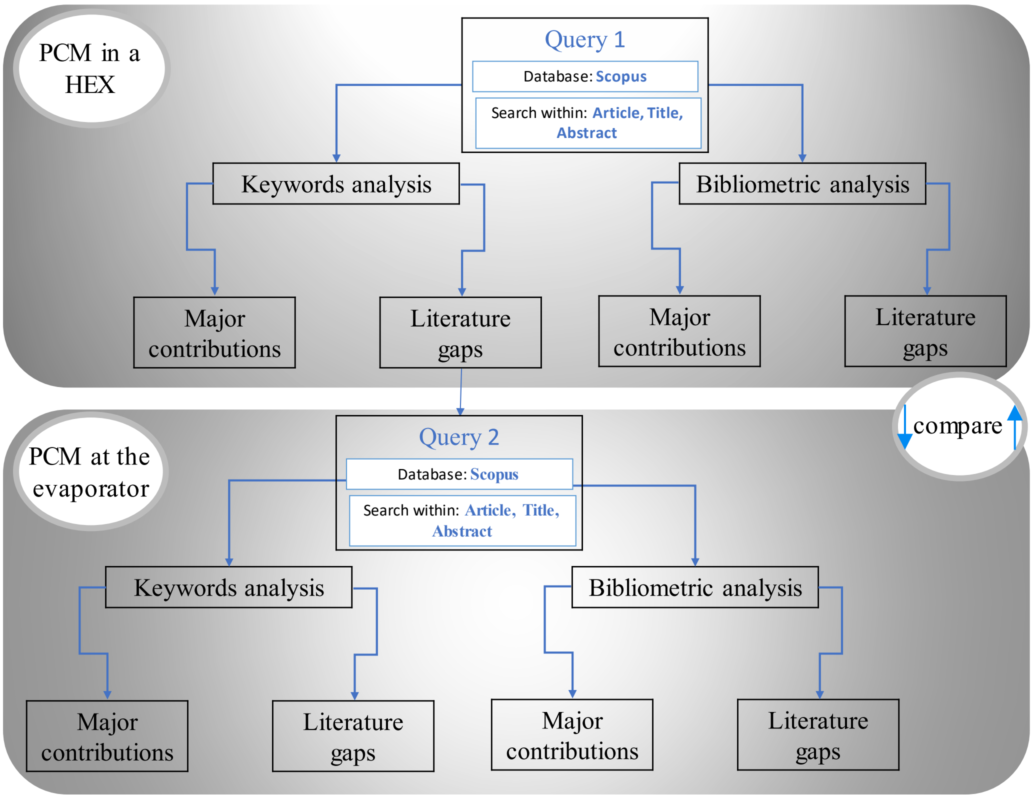


Figure 5. An overview of the methodology applied to analyse the implementation of PCM in HEX.

Query 1 captured 1225 documents while Query 2 captured 46 documents, which is less than 4% of Query 1. In the documents, a total of 6560 and 565 (about 9%) string keywords were identified in Query 1 and Query 2, respectively. The bibliometric data based on the annual number of publications on the topic is presented in Figure 6. From the figure the first publication was realized in 1966 for both queries, but remained dormant with few publications until 2008-2012, when the first peak was observed. From 2013 onwards, the interest in the topic is observed to increase aligning with the current policies encouraging the use of renewable and more sustainable energy systems. Figure 7 presents the main results obtained in the analyses, highlighting the occurrence of subtopics, their links, gaps, and trends in Figure 7a and Figure 7b, for Query 1 and Query 2 respectively. For the trends, the study started with “heat transfer” then shifted to “heat storage”, and recently mainly focused on “storage materials.”

One of the major knowledge gaps is related to the implementation of PCM in practical applications. Keywords that represent practical applications such as “refrigeration”, “air-conditioning”, “heat pump”, and “heating equipment” were observed at the peripheries of the literature maps, meaning the studies had a weak link to practical applications. Even for the integration of PCM at the evaporator, the occurrence of practical application (refrigeration and air-conditioning) was relatively low.

The study conclude that; a huge interest in the topic in the last 10 years with the majority of the contributions as journal papers in reputable journals, a knowledge gap in refrigeration and air-conditioning applications, and uneven distribution of the research outputs.

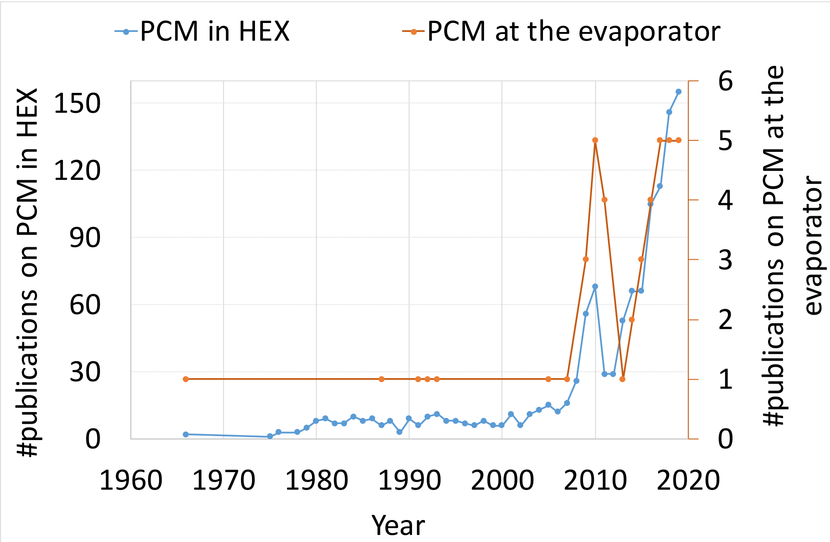
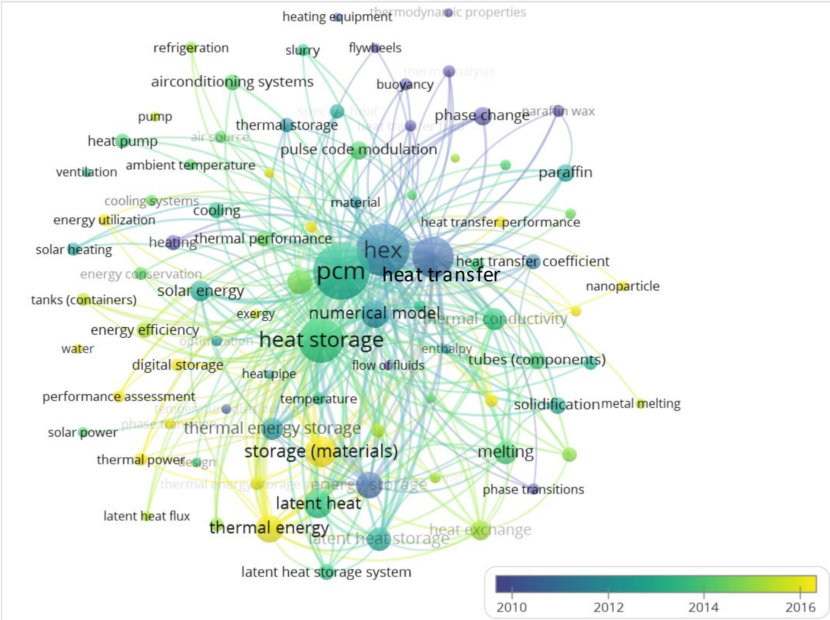
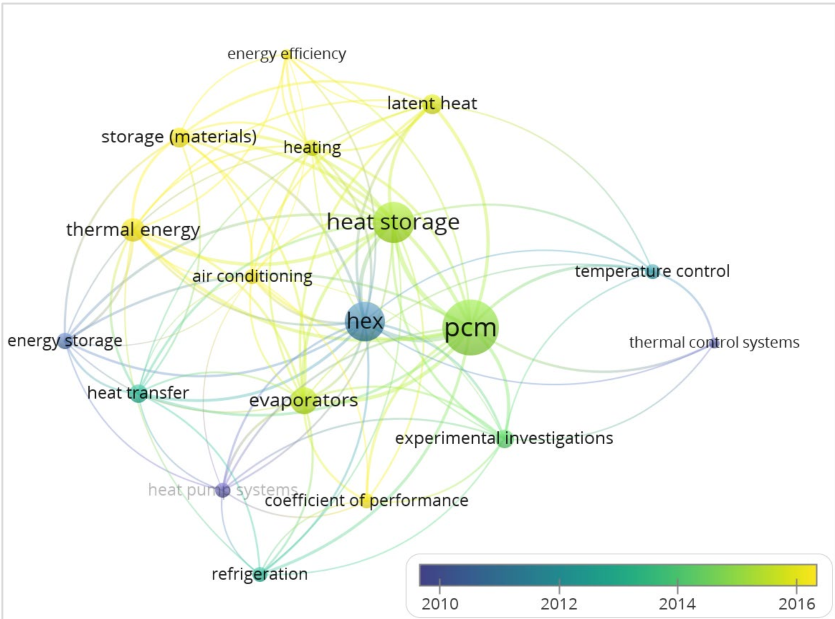


Figure 6. Evolution of annual number of publications.



(a)



(b)

Figure 7. Trends and new perspectives on the integration of (a) PCM in HEX, query 1 (b) PCM at the evaporator, query 2.

1.3.3 Contribution of the candidate

Boniface Dominick Mselle proposed the query string, retrieved the data, analysed and discussed the results, and prepared the manuscript.

1.3.4 Journal paper

The scientific contribution from this research work was published in the Journal of Energy Storage in 2020.

Reference: B.D. Mselle, G. Zsembinszki, E. Borri, D. Vérez, L.F. Cabeza, Trends and future perspectives on the integration of phase change materials in heat exchangers. *J. Energy Storage 2021, 38, 102544, doi: 10.1016/j.est.2021.102544*

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Trends and future perspectives on the integration of phase change materials in heat exchangers

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A R T I C L E I N F O

Keywords:
Thermal energy storage (TES)
Phase change materials (PCM)
Heat exchangers
Bibliometric analysis
Keywords analysis

A B S T R A C T

Traditional review papers provide mainly qualitative information, missing to show the volume, trends, and major contributions in a topic. In response to that, this paper asseses both quantitative and qualitative information regarding the implementation of thermal energy storage using phase change materials in heat exchangers. The data were retrieved from the Scopus database using specific queries relevant to the topic. To investigate the state-of-the-art and research gaps, a keywords analysis was carried out highlighting relevant connections among the major keywords. Moreover, a bibliometric analysis was performed to obtain the trends on the number of publications per year, type of document, authors, affiliation, geographical distribution, journals of publication, and subject areas of research. Based on the keywords and bibliometric analyses, this paper highlights the major contributions and research gaps on the topic.

1.4 PhD objectives

The overwhelming increase of the world population and the ongoing increase of energy demand for various applications call for immediate solutions to attain sustainable energy systems that will slow down climate change and greenhouse gases emissions. In line with this global objective, this thesis is centred on developing new latent thermal energy storage (TES) systems to improve the efficiency of the energy systems, and to increase the renewable energy share in building applications.

To adequately exhaust the topic, the study is divided into specific objectives outlined below.

- To assess the state-of-the-art on the implementation of the active latent TES systems determining the progress, the new perspectives, and the literature gaps in building applications
- To experimentally assess the implementation of new latent TES systems into existing systems and determine their feasibility and optimal operating conditions
- To assess the performance of the new latent TES systems for their implementation into existing systems and provide adequate information on the key features of the systems
- To assess the design features of the new latent TES systems to determine the potential of the features and provide any recommendations to improve the designs

2. Chapter 2: Methodology

This section presents the methodology used to reach the objectives of the thesis, the materials used for the experimental tests, and the structure of the thesis. The methodology applied in this thesis followed two main steps, i.e., first conceptualizing the literature on the topic, then performing lab-scale experimental studies emulating practical applications.

The literature conceptualization was realized using bibliometric and keywords analyses, highlighting both qualitative and quantitative information on the implementation of active latent TES systems for building applications. Here, special attention was given to the major research contributions, the progress, the literature gaps, and the new perspectives on the topic, in particular, the integration of PCM into heat exchangers. Using a specific query relevant to the topic, the data were retrieved from Scopus database, sampled, and analysed reporting the major contributions and the literature gaps. The literature gaps realized in the first query geared to generating a second query that further delved into the topic. The contributions of this study and further details are available in Chapter 1 and Paper 1.

The experimental studies on a laboratory scale delved into the in-depth conceptualization of compact and direct integration of PCM into refrigeration and air-conditioning systems. Here, three novel evaporator-TES modules were tested, and three journal papers were generated from the results. Each module is equipped with unique characteristics of the internal configuration, including the order and the number of the refrigerant, HTF, and PCM channels, allowing evaluation of different features of a TES system, and a heat exchanger. In the first, the external operating conditions for the effective utilization of the modules were investigated through a parametric study and reported in Paper 2. Then a detailed energy analysis at the component level was realized using one of the modules and reported in Paper 3. After that, the influence design features was carried where comparing three distinct configurations assessing the key performance indicators (KPIs) and reported in Paper 4. The contribution of the results in the literature and detailed information are available in the respective papers and in Chapter 3.

2.1 Materials and description of the systems

The novel evaporator-TES modules are made of dense aluminium alloy with high mechanical stability to withstand the volume variations. The modules contain adjacent channels of refrigerant, PCM, and HTF. Each channel contains fins to enhance the heat transfer process. The design of the modules allows three distinct operating modes, i.e. a PCM charging process, a PCM discharging process, and a three-media heat exchange process between refrigerant and HTF through the PCM.

The three configurations of the novel evaporator-TES modules studied are presented in Figure 8a, Figure 8b, and Figure 8c, for TES_1, TES_2 and TES_3 respectively. Figure 8d show the external structure and highlight the dimensions of TES_2, and TES_3. Each module is built up of seven blocks each with a specific task. The dimensions of each part for TES_2, and TES_3 are; block A (300x94x310 mm), block W1 and W2 (60x94x310 mm), block R1 and R2 (45x55x310 mm), and block P1 and P2 (65x55x310 mm). TES_1 contains dimensions similar to the other modules with exception of the height, which is 274 mm instead of 310 mm. The tasks of each component are; block A is designed to enhance the heat transfer process, block P1 and P2 to create extra space to allow volume variation of the PCM, block W1 and R1 for distribution of the HTF and refrigerant, while block W2 and R2 for collecting HTF and refrigerant, respectively.

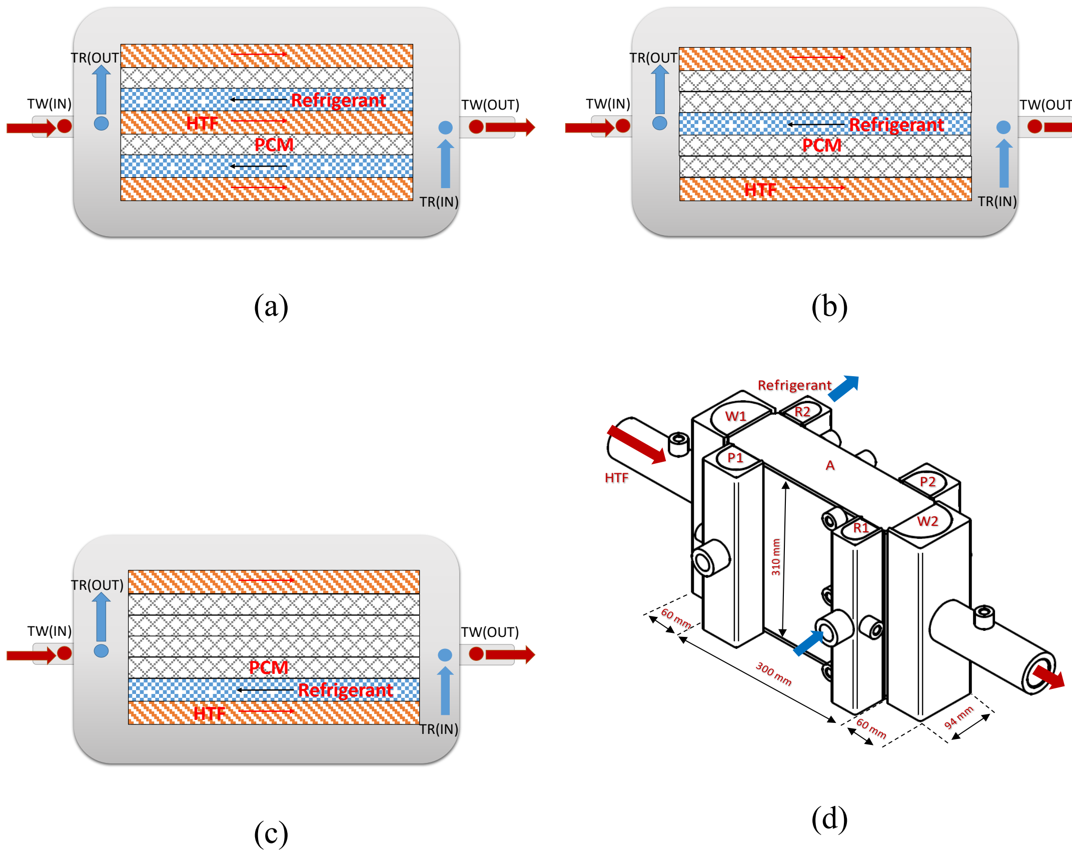

Figure 8. The lab-scale evaporator-TES modules: (a) configuration of TES_1, (b) configuration of TES_2, (c) configuration of TES_3, and (d) dimensions of TES_2 and TES_3

A summary of the characteristics of the modules is reported in Table 2. The construction of the modules mainly consists of aluminium, which accounts for about 75%, while the PCM filled accounts for less than 15% of the total mass. The surface area of heat transfer of TES_1 is more than double that of TES_2 and TES_3.

Table 2. Characteristics of the lab-scale evaporator-TES modules

Module characteristic	TES_1	TES_2	TES_3
Aluminium mass contribution [%]	74	75	75
PCM mass contribution [%]	13	14	14
HTF mass contribution [%]	13	11	11
External volume [m^3]	0.012	0.014	0.014
Total module weight [kg]	24.3	27.0	27.2
Heat transfer surface area [m^2]	0.79	0.34	0.28

Each module was installed in the dedicated test rig shown in Figure 9, mounted at the Universitat de Lleida in Spain, where the lab-scale experimental tests were realized. The system contains two loops, i.e., the refrigerant loop for the charging process, and HTF loop for the discharging process. The refrigeration system is a variable cooling capacity condensing unit (Zanotti model GCU2030ED01B) with a hermetic scroll compressor (CU E scroll digital), air-cooled condenser, and an electronic expansion valve (E2V11ZWF03). According to the manufacturer, the condensing unit has a maximum cooling power of 4.956 kW and a COP of 2.12 when working under an ambient temperature of 32 ºC with a fixed evaporation temperature of −10 ºC. Each module was installed as the evaporator of the system. The second loop consists of a thermostatic bath working with water-glycol mixture as the HTF, equipped with a volume flow meter, a circulation pump, a control valve and stop valves. To minimize the heat/cold losses, all the modules were insulated with 12 cm thick of mineral wool, with thermal conductivity k = 0.04 $W \cdot m^{-1} \cdot K^{-1}$ and density of 65 $kg \cdot m^{-3}$ [19]. Then the UA value for heat losses was estimated experimentally as 0.98 $W \cdot K^{-1}$. This value was then used to minimize the errors in evaluating the energy charged to or discharged from the module.

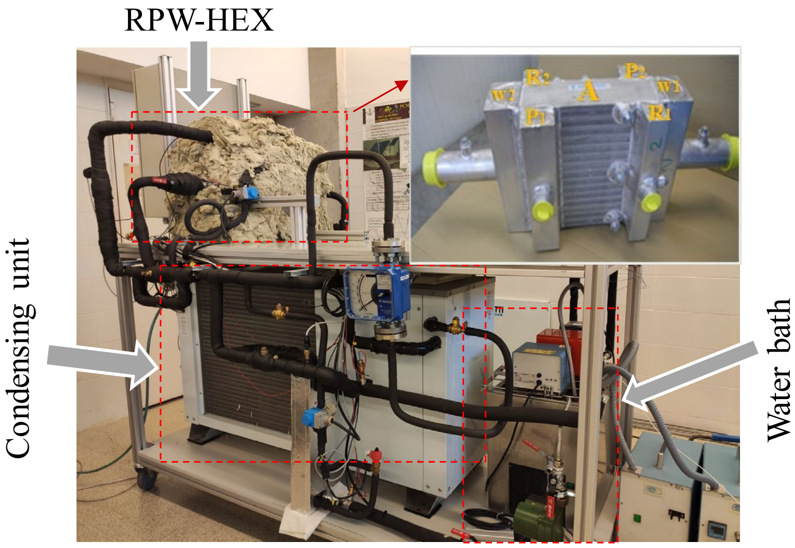

Figure 9. The lab-scale experimental setup

Table 3 summarizes the properties of the PCM and the HTF according to the manufacturer, and to evaluate the energy stored in the container material, the specific heat capacity of aluminium (Cp_{Al}) of 0.9 J·kg^{-1}·K^{-1} from the literature [20] was used.

Table 3. Materials properties

Properties	**RT4 PCM** [21]	**HTF** [22]
Phase change range [°C]	2–4	-18 / 127
Specific heat capacity [kJ·kg^{-1}·K^{-1}]	2	3.6
Density [kg·L^{-1}]	0.88 (solid)	
	0.77 (liquid)	1.05
Thermal conductivity [W·m^{-1}·K^{-1}]	0.2	0.418

For more accurate thermophysical properties, Eq. (1) was derived from differential scanning calorimetry (DSC) experimental results reported in [23] to obtain the enthalpy of the PCM as a function of the temperature.

$$h_{PCM}(T) = \begin{cases} 152.49 + 2.64 \cdot (-4 - T)\ [\mathrm{kJ \cdot kg^{-1}}], & \text{if } T < -4\ ^\circ\mathrm{C} \\ -0.1139 \cdot T^3 - 1.3116 \cdot T^2 - 8.5545 \cdot T + 131.97\ [\mathrm{kJ \cdot kg^{-1}}], & \text{if } -4\ ^\circ\mathrm{C} \le T < 6\ ^\circ\mathrm{C} \\ -0.0985 \cdot T^3 + 2.8732 \cdot T^2 - 28.629 \cdot T + 99.839\ [\mathrm{kJ \cdot kg^{-1}}], & \text{if } 6\ ^\circ\mathrm{C} \le T \le 12\ ^\circ\mathrm{C} \\ -2.38 \cdot (T - 12)\ [\mathrm{kJ \cdot kg^{-1}}], & \text{if } T > 12\ ^\circ\mathrm{C} \end{cases} \quad (1)$$

where $h_{PCM}(T)$ is the specific enthalpy, T is the temperature of the PCM at any instant.

2.2 Theoretical evaluation

To evaluate the energy stored in the module, both the finite volume approach (F.V.A) [24–26] and the law of conservation of energy were applied as highlighted in Figure 10. Here, Figure 10a presents position of the thermocouples and the divisions of the volume elements used in the F.V.A and the energy diagram for the charging and discharging process. The cold energy from the refrigerant loop, E_{ch}, was absorbed into the module as $E_{net,TES,ch}$ and partly lost to the ambient as $E_{loss,ch}$. The net energy charged into the module, $E_{net,TES,ch}$, was then discharged to the HTF as $E_{net,TES,dis}$ and to the ambient as $E_{loss,dis}$.

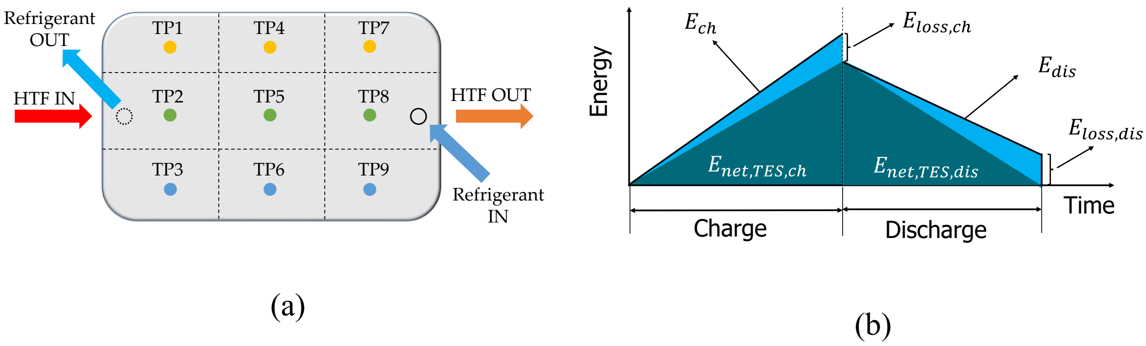

Figure 10. Evaluation of energy stored (a) position of the thermocouples and (b) energy diagram

$E_{net,TES,ch}$ was evaluated using Eq. (2).

$$E_{net,TES,ch} = \sum_{i=1}^{n}\left[m_{PCM,i} \cdot \left(h_{PCM}\left(T_{i,t=t_{ch}}\right) - h_{PCM}\left(T_{i,t=0}\right)\right) + \left(m_{Al,i} \cdot Cp_{Al} + m_{HTF,i} \cdot Cp_{HTF}\right) \cdot \left(T_{i,t=0} - T_{i,t=t_{ch}}\right)\right] \quad (2)$$

where i refers to the volume elements, n is the total number of volume elements, $m_{PCM,i}$ is the mass of PCM, $m_{HTF,i}$ is the mass of HTF, and $m_{Al,i}$ is the mass of aluminium in volume element i, t refers to the time instant, with t_{ch} being the time taken to complete the charging process.

E_{dis} was evaluated using Eq. (3).

$$E_{dis} = \sum_{t=0}^{t_{dis}} \left[\dot{V}_{HTF} \cdot \rho_{HTF} \cdot Cp_{HTF} \cdot \left(T_{HTF,in} - T_{HTF,out}\right)\right]_t \cdot \Delta t + \sum_{t=0}^{t_{dis}} \left[UA_{loss} \cdot (T_a - T_{av})_t\right] \cdot \Delta t \qquad (3)$$

where $\dot{V}_{HTF}$ is the volume flow rate of the HTF, $T_{HTF,in}$ and $T_{HTF,out}$ are the temperatures of the HTF at the inlet and outlet of the module, respectively, t_{dis} is the time taken to complete the discharging process, UA_{loss} is the overall heat transfer coefficient for heat losses, T_a is the ambient air temperature, T_{av} is the average PCM temperature, and $\Delta t = 10$ s is the time interval between two consecutive measurements. Theoretically, the energy stored until the end of the charging process, $E_{net,TES,ch}$ is equal to total energy discharged during the discharging process E_{dis}. Experimentally the results obtained from the two equations were compared obtaining a zero error lower than 2%. Other derivative equations from basic thermodynamic principles [27] were applied to perform each required analysis.

2.3 Thesis structure

The thesis is structured in five chapters as summarized in Figure 11. It includes the overview of the topic, the progress and new perspectives, the methodology, the new contributions/outputs, the main discussions and conclusions, and future recommendations to further exhaust the topic. Each chapter features a specific task and is enriched with information about the whole research process to respond to a secondary objective.

Chapter 1 contains the introduction, the state-of-the-art, and the objectives of the thesis, which cover main issues on global energy, climate change, and sustainable technologies among others. This chapter also contains the first paper of the thesis, which responds to the first specific objective of the thesis.

Chapter 2 presents the methodology applied to develop the thesis and the structure of the thesis. The methodology includes a summary of information on the materials, the experimental test rig, the experimental testing, and the theoretical evaluation methods. However, detailed information on the methodology to reach each specific objective is available in each respective paper attached to the thesis.

Chapter 3 summarizes the contributions of the three papers developed from the experimental results, where each of them focuses on a specific objective. Each subsection contains an overview of the topic, the contribution to the state-of-the-art, the contribution of the PhD candidate, and the main publication information.

Chapter 4 presents the global discussion of the results connecting the outputs of the four papers, reflecting the objectives, and presenting a global interpretation of the outputs as a single entity in the open literature.

Chapter 5 provides the main conclusions driven from the study and the recommendations for future work in the research line.

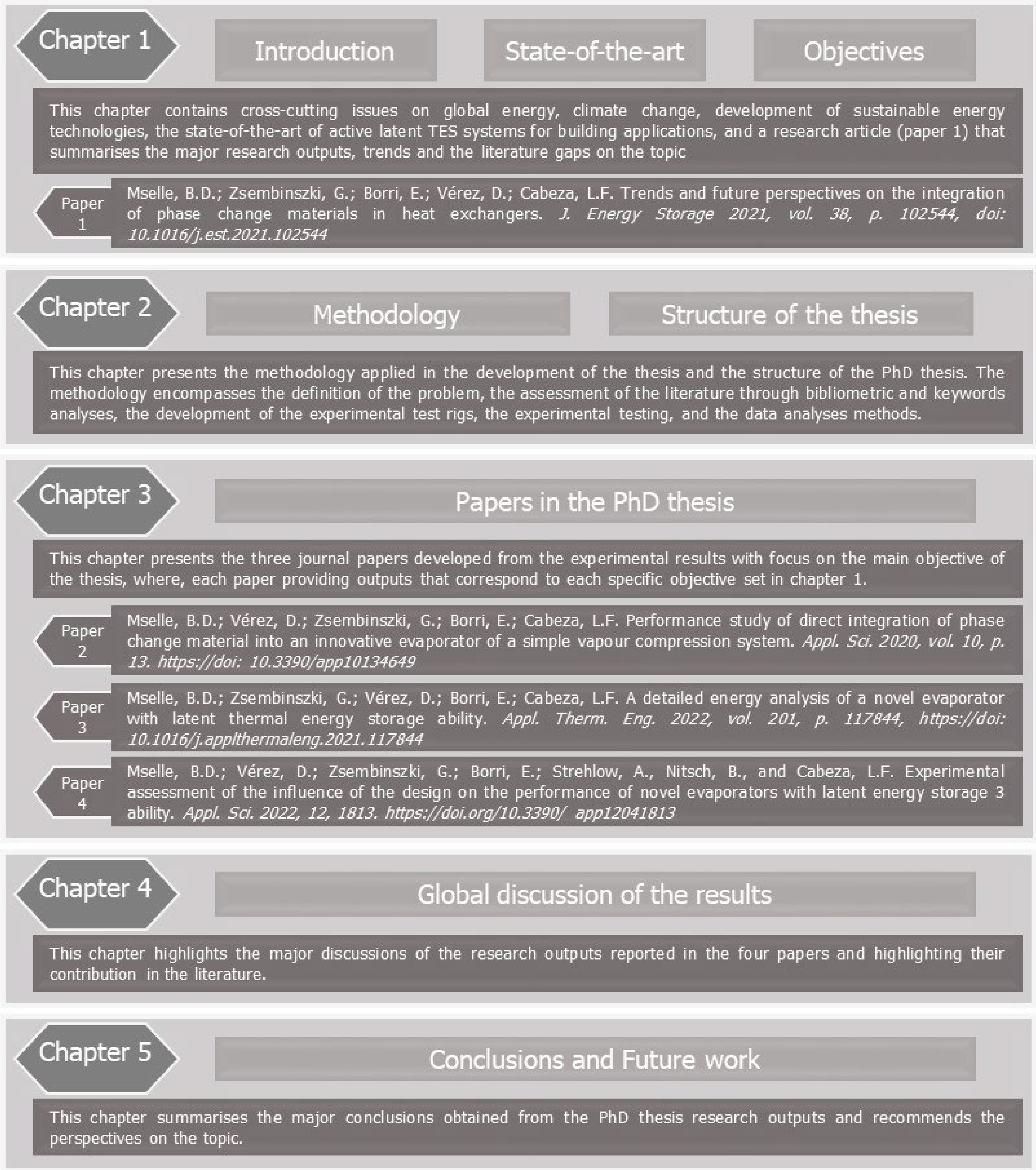

Figure 11. PhD thesis structure by chapters

3. Chapter 3: Papers in the thesis

3.1 Paper 2: Performance study of direct integration of phase change material into an innovative evaporator

3.1.1 Overview

In the open literature, phase change materials (PCM) are reported to be a promising solution for thermal energy storage thanks to their high energy storage density and their ability to store and release energy at near isothermal conditions [13,28,29]. However, their integration into systems for various applications remains to be a challenge given their low thermal conductivity [30]. For refrigeration, heat pumps (HP), and air-conditioning systems, the implementation of PCM is often realized by placing them at the condenser and/or at the evaporator. Cheng et al. [31] studied the integration of PCM into a refrigeration system by wrapping a shape-stabilized PCM at the external tubes of the condenser. The results reported a continuous heat dissipation even after the compressor went off, leading to an increased sub-cooling degree that resulted in an improved coefficient of performance (COP). Wang et al. [32] investigated the influence of placing shell and tube PCM heat exchangers at different positions of the refrigeration cycle. The results indicated an improved COP in all cases and, in particular, when the PCM heat exchanger was placed between the evaporator and the compressor, a lower superheat and stable compressor suction temperature was achieved. Cheng et al. [33] in a numerical model predicted that placing PCM at the evaporator led to lower ON/OFF frequency of the compressor compared to placing them at the condenser, a desirable feature for the compressor lifecycle. Moreover, placing PCM at the evaporator is reported to maintain the temperature of the ambient for a longer period in absence of power supply [34–36].

However, the aforementioned implementations of PCM into the systems lead to increasing the overall number of components, reducing useful space, and increasing the bulkiness of the systems. In response to that, this study was developed with the main focus to develop a novel evaporator for compact and direct integration of PCM into the systems.

3.1.2 Contribution to the state-of-the-art

The study presented a novel refrigerant-PCM-water heat exchanger module as a benchmark for compact and direct integration of PCM into refrigeration and air-conditioning systems. The design of the module is such that PCM channels are in contact with the heat transfer fluid (HTF) and refrigerant passages allowing heat exchange amongst each. For the testing, the module was filled with a commercial PCM (RT4) [37], with a phase change temperature around 4 °C, and was installed into a dedicated experimental setup with two loops. The first loop consists of a compression chiller in which the module acts as an evaporator as it charges the PCM with cold, while the second loop contains the HTF (a mixture of water-glycol) circulating through the module to discharge cold. The PCM was considered completely charged when all thermocouples were at -4 °C, and completely discharged when all the thermocouples were at 12 °C. The scope of the paper included assessing the possible operating modes of the system with the novel evaporator module, and a parametric study on the external conditions while operating the system.

The results are summarized in Table 4 for charging, Table 5 for discharging, and Table 6 for the three-fluids HEX mode. A pronounced stratification effect was noticed in the charging process with a difference of more than 10 °C between the top and the bottom at the end of each test. As a result, the PCM located at the top was partially charged at the end of the process, especially at high compressor powers. This aspect brings awareness of the sizing of the novel module for an intended application. For the tests performed, the optimum performance was observed with the compressor power at 30%. However, to charge the PCM at high compressor power, the evaporation set-point was set at -18 °C (the minimum temperature without freezing of the HTF in the module), instead of -10 °C (the manufacturer recommended optimal set-point). However, although complete charging was achieved at high compressor power when the set-point temperature was lowered, care must be taken not to compromise the performance of the system and the HTF in the module not to freeze. A complete discharging process was achieved at any flow rates tested contrary to the charging process. Such results depict room for improvement of the module for the charging process, in aspects such as the distribution of the refrigerant. For the three-fluids heat exchange operating mode, the results indicated the ability of the module to partially charge or discharge the PCM and maintain thermal equilibrium, therefore acting as a mere evaporator. In this mode, both the refrigerant and HTF were allowed to flow through the module simultaneously. In one case, the process started with the PCM completely discharged (at 12 °C) and, in another case, the process started with the PCM completely charged (at -4 °C). In the first case, results indicated that it is feasible to operate the system at a low HTF flow rate (50 $L \cdot h^{-1}$) and compressor power at 30% or below, while to operate the compression chiller at higher compressor power, a higher HTF flowrate from 100 $L \cdot h^{-1}$ was required. On the contrary, for the second case, only operating the compression chiller at 15% compressor power showed feasible results. Even raising the HTF flowrate to 150 $L \cdot h^{-1}$, did not provide room for operating the system since the evaporation set-point temperature was achieved before sufficient data for analysis was collected. Nonetheless, the paper concluded the feasibility of direct and compact integration of PCM into refrigeration and air-conditioning systems for latent energy storage and indicated the key parameters to be observed for optimal operation of the systems. Moreover, it concluded a high stratification effect in the charging process, displayed a benchmark for different parametric conditions in the three processes, and the operating ranges which address sizing issues.

Table 4. A summary of the charging process at different compressor power

Compressor power [%]	T_top [°C]	T_bot [°C]	T_av [°C]	Energy [kJ]	Time [min]	Power [kW]
15	*3.3*	-8.3	*-2.4*	256.5	31.7	0.13
30	**0.9**	-11.4	**-6.6**	**300.6**	**16.0**	0.31
45	*4.9*	-10.9	*-5.0*	257.8	6.8	0.63
60	*3.7*	-11.2	***-6.6***	**274.0**	5.7	0.80
75	*6.6*	-6.9	*-2.4*	240.3	3.0	1.34

Table 5. A summary of the discharging process at different inlet conditions

	50 [L/h]	100 [L/h]	150 [L/h]
9 [°C]	32	16	10
12 [°C]	26	**12**	9
15 [°C]	27	13	11

Table 6. A summary of results in 3-fluids HEX mode

	PCM initial temperature 12 °C			PCM initial temperature -4 °C		
Compressor power [%]	50 [L/h]	100 [L/h]	150 [L/h]	50 [L/h]	100 [L/h]	150 [L/h]
15	✓	✓	✓	✓	✓	✓
30	✓	✓	✓	X	X	X
45	X	✓	✓	X	X	X
60	X	✓	✓	X	X	X
75	X	X	X	X	X	X

3.1.3 Contribution of the candidate

Boniface Dominick Mselle performed the experiments, analysed and discussed the results, and prepared the manuscript.

3.1.4 Journal paper

The scientific contribution from this research work was published in the journal Applied Sciences in 2020.

Reference: Mselle, B.D.; Vérez, D.; Zsembinszki, G.; Borri, E.; Cabeza, L.F. Performance study of direct integration of phase change material into an innovative evaporator of a simple vapour compression system. *Appl. Sci. 2020, vol. 10, p. 13. https://doi: 10.3390/app10134649*

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Performance Study of Direct Integration of Phase Change Material into an Innovative Evaporator of a Simple Vapour Compression System

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Featured Application: Experimental testing of a novel heat exchanger embedded with thermal energy storage material for refrigeration cycles and air-conditioning systems applications.

Abstract: This paper experimentally investigates the direct integration of 3.15 kg of phase change materials (PCM) into a standard vapour compression system of variable cooling capacity, through an innovative lab-scale refrigerant-PCM-water heat exchanger (RPW-HEX), replacing the conventional evaporator. Its performance was studied in three operating modes: charging, discharging, and direct heat transfer between the three fluids. In the charging mode, a maximum energy of 300 kJ can be stored in the PCM for the cooling capacity at 30% of the maximum value. By doubling the cooling power, the duration of charging is reduced by 50%, while the energy stored is only reduced by 13%. In the discharging mode, the process duration is reduced from 25 min to 9 min by increasing the heat transfer fluid (HTF) flow rate from 50 $L{\cdot}h^{-1}$ to 150 $L{\cdot}h^{-1}$. In the direct heat transfer mode, the energy stored in the PCM depends on both the cooling power and the HTF flow rate, and can vary from 220 kJ for a cooling power at 30% and HTF flow rate of 50 $L{\cdot}h^{-1}$ to 4 kJ for a compressor power at 15% and a HTF flow rate of 150 $L{\cdot}h^{-1}$. The novel heat exchanger is a feasible solution to implement latent energy storage in vapour compression systems resulting to a compact and less complex system.

Keywords: heat exchangers; thermal energy storage (TES); phase change materials (PCMs); refrigeration cycle; cooling applications; experimental study

3.2 Paper 3: A detailed energy analysis of a novel evaporator with latent thermal energy storage ability

3.2.1 Overview

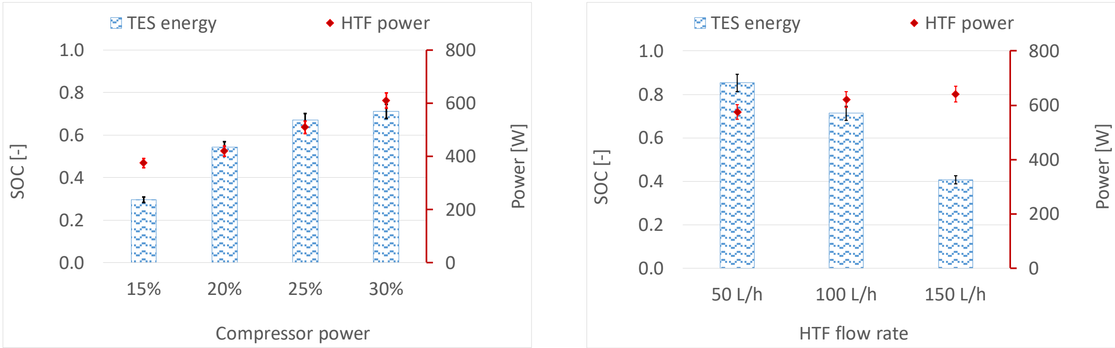
Phase change materials (PCM) are adequate candidates for thermal energy storage in refrigeration, heat pumps (HP), and air-conditioning systems due to their high energy storage density compared to sensible energy storage materials [38]. The implementation of PCMs into practical applications is guided by several requirements and restrictions that determine the overall energy storage density, and their ability to respond to the energy demand and supply-side [13]. In this regard, it is common to see thermal energy storage systems categorized as either passive or active systems. The passive systems are characterized by high overall energy density and slow response to the energy demand and supply, e.g., PCM facades, while the active energy storage systems are characterized by low overall energy storage density and fast response to energy demand and supply, e.g. slurry [39] and heat exchanger type [17,40,41]. For the refrigeration systems, HP, and air-conditioning systems, it is conventional to place PCMs at the external surface of either the condenser or the evaporator, making the implementation closer to passive than active system, a feature that makes the systems suffer more the thermal conductivity drawback.

Given the identified literature gap, this study was developed with the main focus on a novel evaporator module containing PCM embedded between refrigerant and heat transfer fluid (HTF), enhancing the evaporator with active latent energy storage ability in a single component.

3.2.2 Contribution to the state-of-the-art

This paper provided a detailed energy analysis of the novel evaporator with latent energy storage ability, assessing key aspects in TES systems and heat exchangers. Using the optimal testing conditions reported in the previous paper [42], a similar refrigerant-PCM-HEX module was tested. Unlike the previous paper that mainly focused on the influence of the external conditions in charging of the PCM, this paper geared more on the novel module itself, i.e., through a systematic approach covering aspects explicitly on the performance of the module as a TES system and as a heat exchanger, and how it would respond in a practical application. Here, the aspects covered include the total energy stored (including the auxiliary parts), the energy storage contribution of each material, the charging/discharging power, and the cold power delivered to the external loop (HTF loop). Moreover, to assess the feasibility of the module to provide double benefits in a practical application, two types of experiments were performed emulating the variation in the energy source and energy demand sides. In the first case, for a constant cold energy source (from the compression chiller), the influence of different levels of energy demand (HTF inlet flow rate at 0 $L \cdot h^{-1}$, 50 $L \cdot h^{-1}$, 100 $L \cdot h^{-1}$, and 150 $L \cdot h^{-1}$) was assessed. In the second case, for a constant external energy demand (HTF at 12°C and 100 $L \cdot h^{-1}$), the influence of different levels of energy source (compressor power at 0%, 15%, 20%, 25%, and 30%) was evaluated. Furthermore, to assess these key aspects with minimized errors, the study included an experimental assessment of heat losses, the use of the enthalpy curve of the PCM (obtained from laboratory DSC results [43]), and a budget of uncertainty.

The results indicated the feasibility of the module as a TES system (charging and discharging the PCM between -4 °C and 12 °C was achieved) and as a heat exchanger (cold energy from the refrigerant loop was delivered to the external HTF loop after charging the PCM). In a charging and discharging process, more than 50% of the energy was stored in or released from the PCM, although PCM accounted for only 14% of the total weight of the module. The highest charging/discharging power was observed during the phase change period (between –2 °C and 7 °C) and was more than double compared to the average value of the whole process, thanks to the PCM latent energy. Meanwhile, Figure 12 summarizes the influence of different levels of energy demand and energy sources. These results indicate that the state of charge (SOC) and the energy delivered to the HTF loop were dependent on both the energy source and energy demand side. Unlike the charging and discharging processes, where the module was always completely charged or discharged, in the three-fluids HEX operating mode, the module was always partially charged.



(a) (b)

Figure 12. The SOC, TES energy, and HTF power at thermal equilibrium for (a) charging different energy source levels, i.e. different compressor powers, and (b) discharging at different energy demand levels, i.e., HTF flow rates.

3.2.3 Contribution of the candidate

Boniface Dominick Mselle performed the experiments, analysed and discussed the results, and prepared the manuscript.

3.2.3 Journal paper

The scientific contribution from this research work was published in the journal Applied Thermal Engineering in 2022.

<u>Reference:</u> Mselle, B.D.; Zsembinszki, G.; Vérez, D.; Borri, E.; Cabeza, L.F. A detailed energy analysis of a novel evaporator with latent thermal energy storage ability. *Appl. Therm. Eng. 2022, vol. 201, p. 117844, https://doi: 10.1016/j.applthermaleng.2021.117844*

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A detailed energy analysis of a novel evaporator with latent thermal energy storage ability

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A R T I C L E I N F O

Keywords:
Energy analysis
Thermal energy storage (TES)
Phase change materials (PCMs)
Heat exchange
Experimental study

A B S T R A C T

The direct integration of phase change materials (PCM) into refrigeration and air conditioning systems through compact modules is an identified literature gap. In response to the literature gap, this paper provides a detailed energy analysis of a novel compact thermal energy storage module, that allows its direct integration into a refrigeration system as the evaporator. The study addresses key aspects of thermal energy storage (TES) and heat transfer mechanism that complement the previous analyses of the novel concept. Here the total energy stored in the module (including in all auxiliary parts), the charging/discharging power, and the behaviour of the module when used as a TES module and as a heat exchanger (HEX) are assessed. The results demonstrate the feasibility of the module to work as a TES and as a HEX. When working as a TES, complete charging and discharging was achieved, and 54% of the total energy was stored in the PCM although the PCM only accounts for around 14% of the total mass. Moreover, the highest charging/discharging power was obtained within the temperature range where most of the phase change occurred. When the module works as a HEX, it initially charges/discharges partially until a thermal equilibrium is achieved and the level of charge responds to the variation in the energy supply and demand.

3.3 Paper 4: Experimental assessment of the influence of the design on the performance of novel evaporators with latent energy ability

3.3.1 Overview

The compact and direct integration of phase change materials (PCM) into refrigeration, heat pumps (HP), and air-conditioning systems is an identified research gap despite its advantages such as reducing the overall number of components, reducing the bulkiness of the systems, and its minimum use of useful space in comparison to the conventional PCM implementation into the systems. However, in line with decarbonization goals, the call for more green, energy-efficient, and sustainable systems [5,44,45], this research perspective has obtained funding [46] resulting to several outputs in recent years [42,47–52]. The studies developed within the HYBUILD project covered aspects of assessing the optimal operating conditions for efficient charging and discharging of the PCM [42], the various operating modes and the energy storage contribution in the materials consisted in the module [47], the optimal size of the module [50], testing the module in a HP operating in cascade with a sorption system at a demo scale [48], and comparing the hybrid energy storage system with the conventional batteries [46].

However, even with the recent outputs, there is no study dedicated to assessing the design of these new three-media evaporators, something that laid the main motivation for the development of this paper.

3.3.2 Contribution to the state-of-the-art

This paper presented the influence of the configuration/arrangement of the refrigerant, PCM, and HTF channels, an important feature in the design of novel evaporator modules with latent energy storage ability. Three modules with distinct configurations, as shown in Figure 13, were tested and key performance indicators (KPIs) relevant for thermal energy storage systems, heat exchangers, and refrigeration systems were assessed. The first module (TES_1) contains 16 HTF channels, 14 refrigerant channels, and 15 PCM channels, arranged in the order of Refrigerant-PCM-HTF, in such a way that all the fluids were in direct thermal contact (Figure 13a). The second module (TES_2) contains 7 HTF channels, 6 refrigerant channels, and 24 PCM channels, arranged in the order of refrigeran-2#PCM-HTFt, where the refrigerant and HTF channels were not in direct thermal contact with each other, but only in contact with the PCM (Figure 13b). The third module (TES_3) contains 7 HTF channels, 5 refrigerant channels, and 24 PCM channels, arranged in the order of Refrigerant-4#PCM-HTF, similar to the arrangement in TES_1, but with four PCM channels between the refrigerant and HTF channels. In these arrangements, the active surface area of heat transfer in TES_2 and TES_3 was similar, while it was more than double in TES_1.

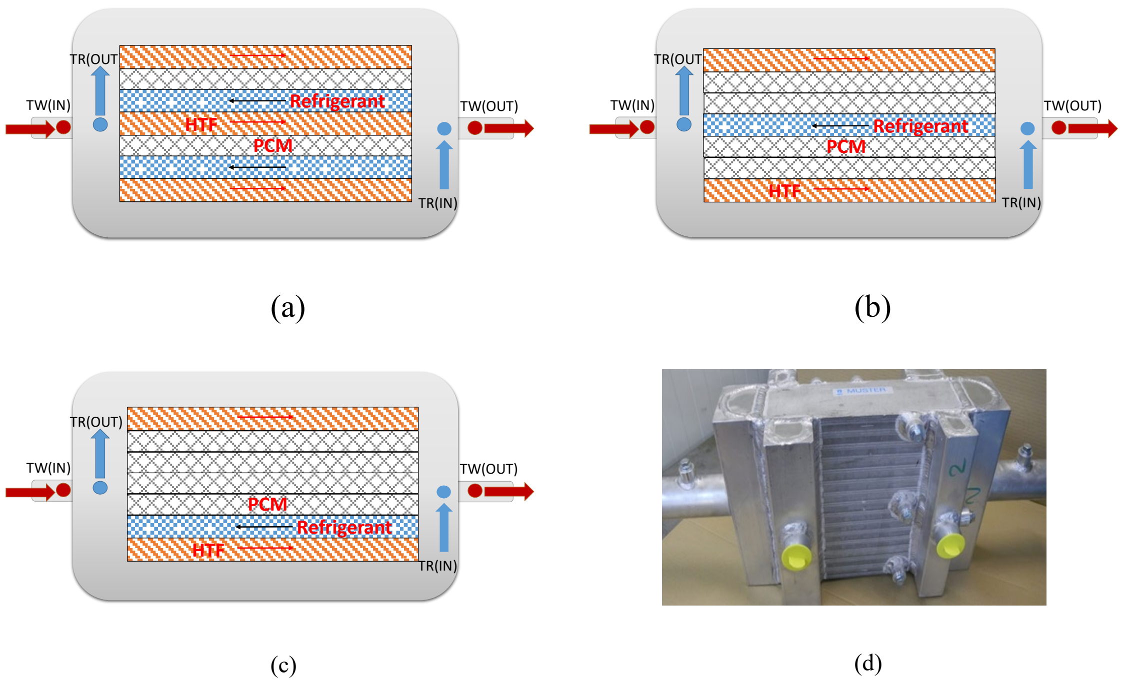

Figure 13. The configuration of the novel evaporator-TES modules: (a) $\boldsymbol{TES_1}$, (b) $\boldsymbol{TES_2}$, (c) $\boldsymbol{TES_3}$, and (d) external structure

The results demonstrated the unique strength of each configuration in terms of the KPIs, from the energy storage capacity, charging power, discharging power, SOC, and effectiveness to the COP of the refrigeration system, as summarized in Figure 14. TES_3 registered the highest energy storage capacity while TES_1 registered the lowest value of this

KPI. This is an expected feature given that TES_1 has less PCM density due to the high number of refrigerant and HTF channels. However, TES_1 presented the highest strength in all the other KPIs, followed by TES_2. This is because TES_1 has more than double heat transfer surface area compared to the other two modules. TES_2 demonstrated a higher performance compared to TES_3 on the discharging process, and the COP, althoughthe two modules contained a similar number of channels. However, these differences indicate the strength of each module and its ability to be used in various applications taking into account the energy profile. For example, TES_1 is suitable for renewable energy driven HP to increase compressor ON/OFF time and respond fast in the intermittent nature of the renewable energy system and energy demand side. TES_2 is recommended for a HP system to increase the compressor OFF time, by providing energy to the demand side at medium effectiveness without compromising the COP. TES_3 is recommended for applications that require high thermal inertia, or places with low availability of electricity, e.g., freezers in vans.

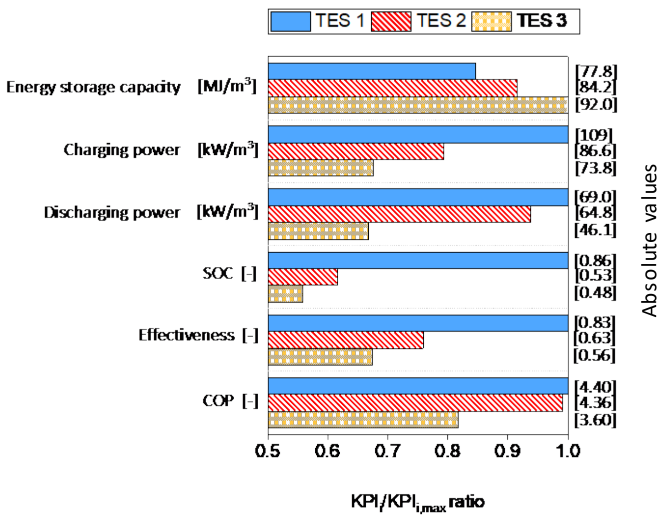

Figure 14. A summary of the key performance of the novel evaporator-TES modules

3.3.3 Contribution of the candidate

Boniface Dominick Mselle performed the experiments, analysed and discussed the results, and prepared the manuscript.

3.3.4 Journal paper

The scientific contribution from this research work was published in the journal Applied Sciences in 2022.

Reference: Mselle, B.D.; Vérez, D.; Zsembinszki, G.; Borri, E.; Strehlow, A., Nitsch, B., and Cabeza, L.F. Experimental assessment of the influence of the design on the performance of novel evaporators with latent energy storage 3 ability. *Appl. Sci. 2022, 12, 1813. https://doi.org/10.3390/*

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Experimental Assessment of the Influence of the Design on the Performance of Novel Evaporators with Latent Energy Storage Ability

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Abstract: This study was carried out within the HYBUILD project, as part of the task aimed at developing novel evaporators for compact and direct integration of phase-change materials (PCM) into air-conditioning systems for efficient utilization of solar energy. To achieve this, novel evaporators were designed to contain PCM between refrigerant and heat transfer fluid (HTF) channels, allowing a three-media heat exchange mechanism. This paper experimentally assesses the influence of the configuration/arrangement of the channels on the performance of the evaporators, using three different lab-scale prototypes. Key performance indicators (KPI) relevant for thermal energy storage (TES) and heat exchangers (HEX) were used to study the influence of the design on the performance of the different designs of the novel evaporators. The results show that the change in the PCM, refrigerant, and HTF channel configuration affects the performance of the novel evaporators independently. The coefficient of performance (COP) of the refrigeration system and the energy storage density of the modules are the least affected KPIs (less than 16%), whereas the state of charge (SOC) at thermal equilibrium is the most affected KPI (about 44%). A discussion on how these effects provide unique strength for specific applications is included.

Keywords: phase-change materials (PCM); thermal energy storage (TES); evaporator design; performance analysis; refrigeration systems

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4. Chapter 4: Global discussion of the results

With the objective of developing compact TES systems for buildings active energy systems within the Net Zero Energy Buildings (NZEB) framework, a novel integration of latent energy storage materials into refrigeration systems was investigated. Conceptually, the outcome is targeted to increase the performance of the system and increase the renewable energy share in buildings energy consumption. The key idea in implementing renewable energy sources into buildings is highlighted in Figure 15. Here, electrical energy is generated from solar energy using photovoltaic (PV) modules and fed to a compression chiller, which then provides space cooling. With the latent TES system integrated, theoretically during peak periods, the space cooling demand would be covered and the extra energy would be stored for later use when no sunlight is available, e.g. during heavy clouds or at night. As part of the overall system, the core of this study focuses on the implementation of thermal energy storage into the systems through compact means with a minimal number of components, and an efficient use of available space.

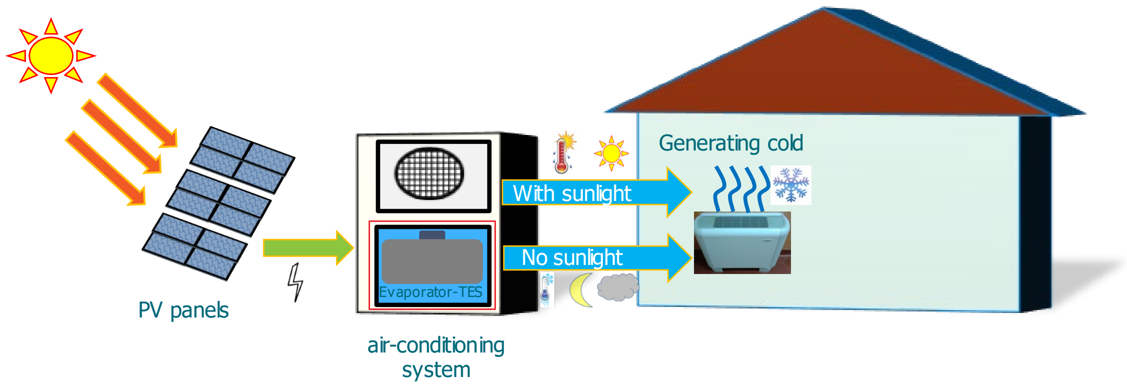

Figure 15. The novel compact hybrid air-conditioning system

The compact integration of latent energy storage material can be realized in a refrigeration system through the two heat exchangers, i.e. condenser and/or evaporator. Implementing it at the condenser improves the performance of the system but is less interesting for cooling application since the energy stored as heat is required to be rejected to the ambient. However, implementing it at the evaporator serves double benefits, i.e. improving the performance of the system and the energy stored as cold is available for later use in space cooling.

In the development of the thesis, the investigation started with the consultation of the state of art on the implementation of PCM into a heat exchanger. Here, the evolution of the topic based on bibliometric and keywords analyses was evaluated, reporting the major contributions, knowledge gaps, trends, and future perspectives. Both conceptual and statistical evaluation was carried out on the publications covering the related topics, the methodology applied (experimental or numerical), renewable energy source (solar energy or waste heat), and building active applications (cooling, heating, air-conditioning, and refrigeration). Moreover, the publications outputs were discussed in terms of documents type (journal article paper, conference paper, etc.), subject area (engineering, energy, etc.), journals of publication, geographical distribution, affiliations, and authors. This type of analysis maps and highlights the main issues on the topic to provide a benchmark for future studies. For example, the analysis by geographical distribution, affiliations, and authors is useful for policymaking and provides information that can trigger cooperation among researchers on the topic. The journals of publications, subject areas, and documents type provide a guideline for the next submissions on the topic. When looking at mapped keywords, information on the evolution of the topic, the relations and links between subtopics, and knowledge gaps become clearer. The divergence of terms that indicate the study of practical applications such as refrigeration and air-conditioning depicts a potential knowledge gap. Adding the term “evaporator” into the query enables screening further specifically for buildings cooling applications. However, the combined evaluation of the statistical and conceptual aspects empowers the understanding of the topic from a wider perspective. However, in line with the identified literature gap, a series of experimental studies was developed accordingly.

The first experimental study on the novel compact and direct integration of latent energy storage materials into active energy systems focused on the external operating conditions of the entire system. A parametric study on one of the modules was carried out in three operating modes, i.e.. charging, discharging, and a three-media HEX mode. This enables evaluating the feasibility of the systems in different operating ranges and conditions. Here, a refrigerant loop is used to charge the PCM with cold while an HTF loop is used to discharge the cold from the PCM. The refrigerant loop is relatively complicated compared to the HTF loop because it contains several security measures based on temperature and pressure to ensure the proper functioning of the system without compromising the compressor. Moreover, given the fact that the refrigerant enters the evaporator as a two-phasefluid, it introduces further complexity in the distribution of the refrigerant. The denser part of the fluid (liquid phase) is deposited at the bottom, subsequently leading to uneven charging, resulting in a pronounced stratification effect inside the module. This effect consequently limits the operating range of the entire system. Although a complete discharge was achieved in all conditions, a partial charging of the PCM was depicted at high compressor power due to a pronounced stratification effect. This impact indicates under-sizing defects, which could lead to minimal use of the refrigeration system in a practical application. In this case, the refrigeration system operates smoothly at compressor power between 15% and 30%. However, this study can be considered as a benchmark for the compact and direct integration of latent TES into the refrigeration system.

In the continuation of the series of experimental studies, a dedicated investigation on the evaporator-TES module was conducted. Here more specific details on the performance of the novel module were evaluated reporting key performance indicators (KPIs) for a TES system and a heat exchanger. Given a module with more than 75% of the construction material (aluminium), and with less than 14% percent of PCM, an evaluation of the contribution of each material is required to identify the TES potential of each material in the module and highlight any room for design improvement. Here, the finite volume approach was utilized to reduce errors that result from the ununiform charging due to the stratification effect. The study emulated practical applications considering a varying energy source and energy demand. In the first case, the energy source (compressor power) was maintained constant to test the performance of the module at different levels of external energy demand (HTF flow rate). In the second case, the energy demand was maintained constant as the energy source was set at different levels. Here, the ability to charge the PCM in each case and the feasibility of resolving the mismatching conditions between the energy source and energy demand were manifested. If the results are translated to a real application, it means the PCM would charge completely when there is no external energy demand, and discharge completely when there is no external energy source. In a case with both energy demand and source, the PCM would charge partially, being the level of energy stored in the module dependent on the relative relationship between energy source and demand. For example, during the peak moment of solar irradiation, a high energy level would be attained in the module after covering for the demand, and in case a higher energy demand occurs, the extra energy would be provided by what was stored in the module.

Lastly, an experimental study dedicated to assessing the performance of the novel evaporator-TES modules was carried out based on the internal configuration of the refrigerant, PCM, and HTF channels. Here the KPIs of three modules were investigated in terms of TES systems, heat exchangers, and the overall refrigeration system. Each configuration presented a distinct performance, indicating the room for further improvements of the modules, and indicating the ability of the modules to be optimized for various applications such as HP, air-conditioning systems, and refrigeration systems.

In summary, throughout the investigations in this thesis, major aspects of the integration of latent energy storage into active energy systems for buildings applications covered are outlined below:

- An overview of the integration of PCM in a heat exchanger, in general, and at the evaporator of a refrigeration system, in particular, connecting between statistical and conceptual information and highlighting the major outputs, knowledge gaps, trends, and new perspectives.
- A benchmark for direct integration of PCM into refrigeration cycle, covering external conditions for the optimal charging and discharging of PCM, and discussing issues related to sizing of the modules and the distribution of the refrigerant.

- A detailed assessment of a novel evaporator-TES module from energy storage and heat exchanger perspectives at a module level, pointing out the contribution of each material in the module and including the auxiliary parts of the module.
- Expanded performance analysis of three modules with three distinct configurations to assess the impact of design on the performance of the technology at module level and overall system level.

5. Chapter 5: Conclusions and future work

5.1 Major conclusions

In line with the primary goal of developing new energy systems for sustainable development, four dedicated investigations were carried out and published as scientific journal papers. Each paper answered to a specific secondary objective consequently drawing the conclusions summarized below.

In the first study, aimed atassessing the state of the art and conceptualizing on the topic to build a foundation of the investigation through identifying progress, trends, new perspectives, and knowledge gaps, the following conclusions were drawn:

- The topic attained the highest growth in the last ten years.
- The majority of the studies are not linked to practical applications for buildings energy consumption.
- The evolution on the topic started with a focus on heat exchange mechanisms and shifted to storage materials in recent years.
- The majority of the scientific outputs on the topic were published as journal papers, in the engineering subject area in the journal of Applied Thermal Engineering.
- The studies focused on the utilization of renewable energy sources starting with solar energy and shifting focus to waste heat recently.
- The topic was developed relatively equally through experimental and numerical methods.

In line with the identified knowledge gap, the series of experimental investigations carried out to respond to the primary objective are concluded below. The first in the series of experimental studies, aimed at evaluating the external conditions for operating the system, concluded that:

- The stratification effect highly affects the charging process (through the refrigerant) in comparison to the discharging process (through the water-glycol).
- Lower compressor power leads to a more uniform PCM charge.

- The energy stored at the PCM until the security set-point is reached depends on the compressor power.
- Both high HTF inlet temperature and high flow rate increase the discharging power linearly.
- For the undersized evaporator-TES module, the three-media HEX mode acquires a higher operating range by increasing the HTF flow rate.
- Increasing the HTF flow rate increases the operating range of an undersized module in three-media HEX mode.

In the second experimental study that aimed at evaluating at a component level covering key concepts on thermal energy storage systems and heat exchangers, it was concluded that:

- A complete charging and discharging are viable within the right dimensions of the evaporator-TES module and refrigeration system.
- The charging power and discharging power increase linearly by increasing compressor power and HTF flowrate, respectively.
- The average charging/discharging power during the phase change period is more than double the average power of the entire process..
- The PCM energy storage density was more than six times that of the sensible energy material in the module (aluminium and HTF combined).
- In three-media HEX mode, the module acquires a thermal equilibrium while charged partially.
- The state of charge of the module at thermal equilibrium is directly proportional to the compressor power (energy source) and inversely proportional to the HTF flow rate (energy demand).

Finally, the last experimental study dedicated to assessing the performance of the modules when designed with different internal configurations of the refrigerant, PCM, and HTF channels concluded that:

- Each performance indicator is affected independently from one configuration to another.

- The energy storage density and COP are the least affected performance indicators and can vary until 16%.
- The charging/discharging power varies moderately from one configuration to another, at a maximum of 35% of variation.
- The SOC at thermal equilibrium is the most affected performance indicator from one configuration to another and can vary up to 44%.

5.2. Future work

Although the study covered many aspects of thermal energy storage, heat exchange, and refrigeration systems, some issues require a deeper study in the future to take maximum advantage of the new technology. The proposed future studies include:

- Implementing the system in a real application and observing the performance in a building energy consumption profile with an integrated renewable energy system.
- Implementing a control strategy to optimize energy storage and respond efficiently to the energy demand and energy source.
- Assess the materials durability, compatibility, and performance of the system in a long term.
- Techno-economic analysis to assess the benefits of the technology and its role in sustainable development.

Other research activities

Other journal publications

The PhD candidate carried out other scientific research besides the one presented in this thesis during the execution of his PhD. The resulting publications are listed below:

1. Zsembinszki, G.; **Mselle, B.D.;** Vérez, D.; Borri, E.; Strehlow, A.; Nitsch, B.; Frazzica, A.; Palomba, V.; Cabeza, L.F. A New Methodological Approach for the Evaluation of Scaling Up a Latent Storage Module for Integration in Heat Pumps. *Energies 2021, vol. 14, p. 7470, https://doi: 10.3390/en14227470*
2. Vérez, D.; Borri, E.; Crespo, A.; **Mselle, B.D.;** de Gracia, Á.; Zsembinszki, G.; Cabeza, L.F. Experimental Study on Two PCM Macro-Encapsulation Designs in a Thermal Energy Storage Tank. *Appl Sci 2021;11:6171. https://doi.org/10.3390/app11136171.*

Contributions to conferences

1. **Mselle BD;** Zsembinszki G; Vérez D; Cabeza LF (2021). Experimental study of a novel three-fluids heat exchanger embedded with phase change materials for cooling applications. *En EnerSTOCK 2021 - 15th International Virtual Conference on Energy Storage. Book of abstracts . (pp. 209 - 209) . 104212 - University of Ljubljana . ISBN: 978-961-6104-49-4.*
2. Vérez D; Borri E; Crespo A; **Mselle BD;** de Gracia A; Zsembinszki G; Cabeza LF (2021). Experimental study on the effect of flat and thin slab encapsulation design on a PCM tank. *En EnerSTOCK 2021 - 15th International Virtual Conference on Energy Storage. Book of abstracts. (pp. 115 - 115). 104212 - University of Ljubljana. ISBN: 978-961-6104-49-4.*
3. Palomba V; **Mselle BD**; Vérez D; Borri E; Varvaggiannis S; Monokrousou E; Nitsch B; Strehlow A; Barmparitsas N; Leontaritis A; Bonanno A; Dino G; Zsembinszki G; Karellas S; Frazzica A; Cabeza LF (2021). Experimental comparison of small-scale and full-scale latent storage for integration in efficient heat pumps. *En EnerSTOCK 2021 - 15th International Virtual Conference on Energy Storage. Book of abstracts . (pp. 187 - 187) . 104212 - University of Ljubljana . ISBN: 978-961-6104-49-4.*

4. Zsembinszki G; Vérez D; **Mselle BD;** Borri E; Cabeza LF (2021). Methods for the determination of the state-of-charge of a thermal energy storage device. *En EnerSTOCK 2021 - 15th International Virtual Conference on Energy Storage. Book of abstracts . (pp. 138 - 138) . 104212 - University of Ljubljana . ISBN: 978-961-6104-49-4.*

Contributions to seminars and workshops

5. European Researchers' Night 2021. Poster "Desarrollo de nuevos sistemas de almacenamiento de energía térmica" in the "La nostra recerca" section.
6. RedTES, Seminario virtual. "Nuevos desarrollos en almacenamiento térmico para la descarbonizacion de la industria"
7. European Researchers' Night 2021. Taller "El viatge de l'energia, des del Sol fins a la teva dutxa"
8. RedTES, poster oral presentation. "New thermal energy storage systems for building applications"

Others activities

Teaching

- Sustainable Construction 2 at Universitat de Lleida from 2020 until 2022.

Projects participation

1. Innovative compact HYbrid electrical/thermal storage systems for low energy BUILDings (Efficient Buildings). 2017 - 2022. Ref.768824. European Union. IP: Luisa F. Cabeza. (16 researchers)
    - Buildings
    - Thermal energy storage
    - Renewable energy
    - Energy Efficiency

- Industry

2. Methodology for analysis of thermal energy storage technologies towards a circular economy (MATCE). Ministerio de Ciencia, Innovación y Universidades de España, RTI2018-093849-B-C31 - MCIU/AEI/FEDER, UE, 2019-2021.
3. Red española en almacenamiento de energía térmica (Xarxa d'excel·lència). 2020 - 2022. Ref.RED2018-102431-T. Ministerio de Economía, Indústria y Competitividad. IP: Luisa F. Cabeza. (37 researchers)
    - Thermal energy storage
    - Leadership
4. GREiA. Grup de Recerca en Energia i Intel·ligència Artificial (Ajuts de suport a la recerca de grups i xarxes). 2017 - 2021. Ref.2017 SGR 0153. Departament d'Economia i Coneixement (Generalitat de Catalunya). IP: Luisa F. Cabeza. (24 researchers)
    - Energy efficiency
    - constructive solutions
    - Sustainability
    - Artificial intelligence
    - Energy
5. Catalan European Researchers' Night (EUNightCat20) (Curie Actions Night (MSCA-NIGHT)). 2020 - 2021. Ref.954506. Unión Europea. IP: Luisa F. Cabeza. (15 researchers)

6. Organizing committee participation

1. Researchers' Night 2019, 14th edition 2019. Lleida, Spain.
2. Researchers' Night 2020, 15th edition 2020. Lleida, Spain
3. Researchers' Night 2021, 16th edition 2020. Lleida, Spain

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