Universitat de Lleida

COLD THERMAL ENERGY STORAGE (CTES) FOR LNG ENERGY SYSTEMS

Lizhong Yang

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Universitat de Lleida

TESI DOCTORAL

COLD THERMAL ENERGY STORAGE (CTES) FOR LNG ENERGY SYSTEMS

Lizhong Yang

Memòria presentada per optar al grau de Doctor per la Universitat de Lleida Programa de Doctorat en Informàtica i Enginyeria Industrial

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Departament d'Informàtica i Enginyeria Industrial
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COLD THERMAL ENERGY STORAGE (CTES) FOR LNG ENERGY SYSTEMS

Memòria presentada per optar al grau de Doctor per la Universitat de Lleida redactada segons els criteris establerts en l'Acord núm. 67/2014 de la Junta de Govern del 10 d'abril de 2014 per la presentació de la tesis doctoral en format d'articles.

Programa de doctorat: Enginyeria i Tecnologies de la Informació

Directors de la Tesis: Dra. Luisa F. Cabeza, Dr. Alessandro Romagnoli, i Dr. Antoni Gil

La Dra. Luisa F. Cabeza, catedràtica de l'Escola Politècnica Superior de la Universitat de Lleida, el Dr. Alessandro Romagnoli, professor associat de la Nanyang Technoligical University, i Dr. Antoni Gil, investigador sènior de la Nanyang Technoligical University.

CERTIFIQUEN:

Que la memòria "Cold Thermal Energy Storage (CTES) for LNG Energy Systems" presentada per Lizhong Yang per optar al grau de Doctor s'ha realitzat sota la seva supervisió.

Lleida, Mar 2022

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SUMMARY

The global demand for cold energy for residential, commercial, and industrial applications accounts for a considerable portion of final energy consumption and carbon emissions. However, some high-grade cold energy sources, such as the cold energy released during the regasification process of liquefied natural gas (LNG), are generally wasted. This thesis focuses on developing cold thermal energy storage (CTES) technologies for LNG energy systems. Through a comprehensive literature review, we identified the lack of comprehensively designed and built CTES units for LNG cold energy utilization, proper heat transfer enhancement techniques, and quantitative analysis of the contribution of CTES in LNG energy systems. Therefore, this thesis mainly contains three parts: 1) the development of a comprehensive CTES design method, 2) application of the design method in the designing of an LNG energy system, and 3) development of a heat transfer enhancement technique for CTES units. These investigations make use of experimental, numerical, and optimization methodologies. By integrating multi-criteria material assessment with efficient geometry optimization, the design method was shown to be fast and reliable for the preliminary design of latent heat shell-and-tube CTES units. Using the design method, we designed an integrated organic Rankine cycle (ORC) system that uses the low-grade geothermal energy from an abandoned exploitation well and the waste cold energy from a satellite LNG station. When equipped with the CTES, the ORC efficiency and net power production rose by more than 30% and 25%, respectively. A graphite sheet-based macrofiller was designed to enhance the heat transfer. To measure its effective thermal conductivity (k_{eff}), a numerical, experimental, and Bayesian optimization-based method was developed. The method was proved to be fast and accurate, and the macrofiller design increased the k_{eff} by around 20% and suppressed subcooling.

RESUMEN

La demanda global en refrigeración en aplicaciones residenciales, comerciales y industriales representa hoy en dia una parte considerable de la energía final consumida y de las emisiones de CO_2. Aún así, algunas fuentes de frío de alto grado, como el frío que se libera durante la regasificación del gas natural licuado (GNL), es enviado a la atmósfera sin ser usado. Esta tesis doctoral está enfocada en el estudio y desarrollo de tecnologías de almacenamiento de frio (CTES, por sus siglas en ingles) aplicadas a la regasificación del GNL. A través de una exhaustiva revisión de la literatura publicada hasta el momento, se ha identificado una falta de comprensión en el proceso de diseño y construcción de unidades para CTES, asi como técnicas adecuadas para mejorar el coeficiente de transferencia de calor, y de algún tipo de herramienta de análisis cuantitativo respecto a la posible contribución de los sistemas CTES en estaciones regasificadoras de GNL. En consecuencia, esta tesis consta de 3 partes: 1) desarrollo de un método comprensivo de diseño de sistemas CTES; 2) aplicación de este método de diseño a un sistema de regasificación de GNL; 3) desarrollo de una técnica de mejora del coeficiente de transferencia de calor en sistemas CTES. A través de la integración de métodos multi-criterio de mejora del material, y mediante una eficiente optimización de la geometría del prototipo, este nuevo método ha demostrado ser rápido y fiable en el diseño preliminar de sistemas CTES basados en el concepto de intercambiador de carcasa y tubos. Este método ha permitido diseñar un sistema integrado basado en un ciclo orgánico de Rankine (ORC) que extrae el calor de una fuente geotérmica de una explotación petrolera abandonada, y el frio de una estación satélite de GNL. Una vez equipado con el sistema CTES, el ORC incrementa su eficiencia en más de un 30% y en un 25% la capacidad de producción. Para la mejora del coeficiente de transferencia de calor se ha diseñado un sistema que utiliza láminas de grafito. Para la medida de la conductividad térmica efectiva del sistema se ha desarrollado un método rápido y preciso, basado en optimización numérica, experimental y Bayesiana, los resultados de la cual han demostrado que las laminas de grafito incrementan la conductividad térmica efectiva en un 20% mientras reducen el efecto del subcooling.

RESUM

La demanda global en refrigeració en aplicacions residencials, comercials i industrials representa avui en dia una porció considerable de l'energia final consumida i del CO_2 emès. Tot i així, algunes fonts de fred d'alt grau, com el fred que s'allibera durant el procés de regasificació del gas natural liquat (GNL), és enviat a l'atmosfera sense treure'n cap profit. Aquesta tesi doctoral està enfocada en l'estudi i desenvolupament de tecnologies d'emmagatzemament de fred (CTES, per les sigles en anglès) aplicades a la regasificació de GNL. A través d'una exhaustiva revisió de la literatura publicada fins al moment en aquest camp, s'ha identificat una manca de comprensió en el procés de disseny i construcció d'unitats per CTES, així com tècniques adequades per millorar el coeficient de transferència de calor i d'algun tipus d'eina d'anàlisi quantitatiu respecte a la possible contribució dels sistemes CTES en estacions regasificadores de GNL. En conseqüència, aquesta tesi consta de 3 parts principals: 1) desenvolupament d'un metode comprensiu de disseny de sistemes CTES; 2) aplicació d'aquest mètode de disseny a un sistema de regasificació de GNL; 3) desenvolupament d'una tècnica de millora del coeficient de transferència de calor en sistemes CTES. Mitjançant la integració de mètodes multi-criteri de millora del material i amb una eficient optimització de la geometria del prototip, el nou mètode de disseny ha demostrat ser ràpid i fiable pel disseny preliminar de sistemes CTES basats en el concepte d'intercanviador de carcassa i tubs. Aquest mètode ha permès dissenyar un sistema integrat basat en un cicle orgànic de Rankine (ORC) que extreu la calor d'una font geotèrmica d'una explotació petroliera abandonada, i el fred d'una estació-satèl·lit de GNL. Un cop equipat amb el sistema CTES, l'ORC incrementa la seva eficiència en més d'un 30% i la capacitat de producció en un 25%. Per a la millora del coeficient de transferència de calor s'ha dissenyat un sistema que utilitza làmines de grafit. Per a mesurar la conductivitat efectiva del sistema s'ha desenvolupat un mètode ràpid i precís, basat en optimització numèrica, experimental i Bayesiana, els resultats del qual han demostrat que les làmines de grafit incrementen la conductivitat tèrmica efectiva en un 20% i redueixen l'efecte del subcooling.

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LIST OF ABBREVIATIONS AND ACRONYMS

AEW	Abandoned exploitation well
CTES	Cold thermal energy storage
D	Diameter
DI	De-ionized
f.o.b.	Free on board
FVM	Finite volume method
GA	Genetic Algorithm
H	Height
HTF	Heat transfer fluid
IEA	International Energy Agency
IRENA	International Renewable Energy Agency
k_{eff}	Effective thermal conductivity
L	Length
LHTES	Latent heat thermal energy storage
LNG	Liquefied natural gas
MADM	Multi-attribute decision making
MODM	Multiple objective decision making
NIST	National Institute of Standards and Technology
PCM	Phase change material
ORC	Organic Rankine cycle
RMSE	Root-mean-square error
TES	Thermal energy storage

W	Width

1 INTRODUCTION

1.1 Research background

1.1.1 Mismatch between cold energy demand and supply

1.1.1.1 Increasing demand for cooling and refrigeration

Heating and cooling for residential, commercial, and industrial applications account for a substantial proportion of the global final energy consumption [1]. According to the International Renewable Energy Agency (IRENA) and International Energy Agency (IEA), heating and cooling are the most critical energy end-uses, accounting for around half of global final energy consumption and more than 40% of energy-related CO_2 emissions [2]. In the residential sector, particularly, the share of heat and cooling in the end-use energy consumption can exceed 60% in Europe and the United States [3,4]. In some hot climates, such as parts of the Middle East, Southeast Asia, and North America, cooling energy alone can be greater than all other end-use energies combined [5,6]. Moreover, due to climate change, population growth, urbanization, and economic development, demand for heating and cooling will continue to rise rapidly in the following decades [2,7,8], with cooling being the primary driving force.

Currently, heating still outweighs cooling in the share of final energy consumption. However, the cooling demand is gradually catching up. Since the 1990s, the cooling demand has already tripled [2], making it the fastest-growing use of energy in buildings [9]. The energy used for cooling buildings in Europe may increase by 72% in 2030 compared to 2015, while the demand for heating will drop by 30% [1]. Globally, the space cooling energy demand can triple in the next 30 years [6] (as illustrated in Figure 1.1). By around 2060, the demand for cooling may exceed heating [10]. By 2100, the electricity consumption for refrigeration, air-conditioning, and heat pump equipment can be as much as 33 times the level of 2015, totaling more than 10,000 TWh [8].

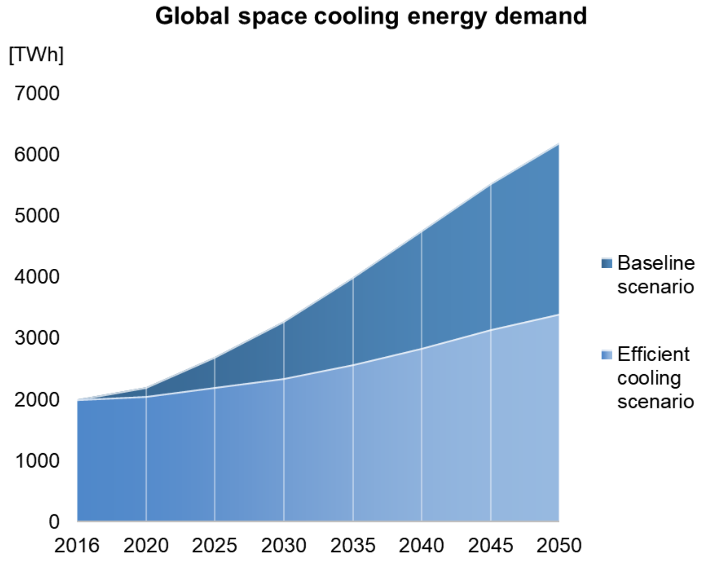


Figure 1.1: Global space cooling energy demand. (Data source: IEA [6])

Therefore, decarbonization of the cooling and refrigeration industry is crucial in the future energy transition for climate mitigation.

1.1.1.2 LNG as an alternative cold source

Meanwhile, some cold energy sources remain insufficiently utilized despite the urgent demand for emission-free cooling and refrigeration energy. The most widely studied alternative cold source is liquefied natural gas (LNG).

By cooling down the natural gas to its liquid phase around -162°C, LNG is a low-cost, easy, and safe way of gas transportation and storage [11]. According to the prediction of IEA [12], by the late 2020s, LNG may overtake pipelines as the primary means of gas trading between regions since it is the only economically feasible modal for gas transportation with a distance of above 400 km [13]. Despite the recent investment halts due to pandemic-related economic crisis, recently published data from Royal Dutch Shell [14] shows that the global demand for LNG imports will double by 2040, mainly driven by the strong growth in Asia and Europe [14].

During the regasification process of LNG at the receiver terminals, a significant amount of cold energy (around 830 kJ/kg of LNG) is usually released to the ambient air or seawater in the evaporators. If properly used, the high-grade (low-temperature) cold energy conceived in LNG can be transported to the end users and supply a wide range of applications, such as cryogenic power generation, space and industrial process cooling, cold supply chain, air separation, seawater desalination, and waste treatment [15–17], leading to a future LNG-based cold economy as illustrated in Figure 1.2 [7]. In recent years, extensive studies have focused on various technologies about LNG cold energy utilization [17]. However, LNG cold energy is still generally wasted in most LNG terminals around the globe [17,18], leaving a vast potential for these proposed technologies to be deployed in real applications.

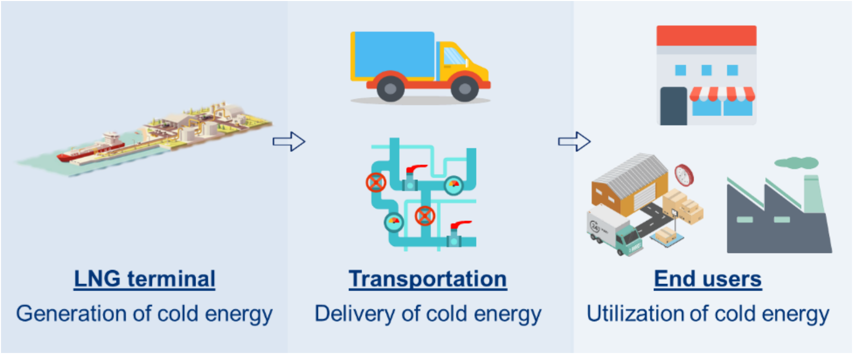


Figure 1.2: The process of generation, transportation, and utilization of LNG cold energy [19].

Meanwhile, few studies addressed the problems of the uneven distribution of the LNG cold energy, both spatially and temporally. Most cold energy users in the metropolitical and industrial areas inland are located at a distance from the coastal LNG terminals (ranging from a few kilometers to thousands of kilometers) and suffer from highly fluctuating natural gas demand profiles [20–22]. Since the top priority of an LNG terminal is to satisfy the demand of the gas grid, LNG cold energy is not generated according to the cooling demand profiles. Therefore, technologies that can deliver the LNG cold energy from the terminals to the users, and decouple the cold energy demand from its supply availability, have the potential to considerably improve the economic feasibility of LNG cold energy utilization.

1.1.2 Cold thermal energy storage (CTES)

These research gaps lead to the need to develop high-efficiency and low-cost cold thermal energy storage (CTES) technologies suitable for LNG cold energy utilization purposes. Being able to store the LNG cold energy and use it in another location or time, CTES can bridge the spatial and temporal mismatch between the cold energy demand and supply.

In an LNG-based cold economy, CTES has the potential to benefit all cold energy suppliers and users [19]. For the LNG terminal, CTES can help capture the LNG cold energy and supply it to the users on-demand regardless of the varying supply. For the cold energy delivery, CTES units can be engineered to transport cold energy for short distances using land transportation. For the end-users, CTES can increase the efficiency and decrease the operational cost of the refrigeration systems; it can also act as a redundant cold source during emergency cases.

IRENA's prediction shows that the global CTES capacity should double to meet the cooling demand in 2030 [23]. However, using CTES in LNG-based energy systems has not been thoroughly studied. As illustrated in Figure 1.3, this thesis first systematically and comprehensively reviewed the state-of-the-art CTES materials, containment and heat transfer methods, and applications at sub-zero temperatures and pointed out the research directions in these fields. Partial results of the presented work in this section have been published in *Applied Energy* [7], and the main conclusions of the review are summarized in Figure 1.4.

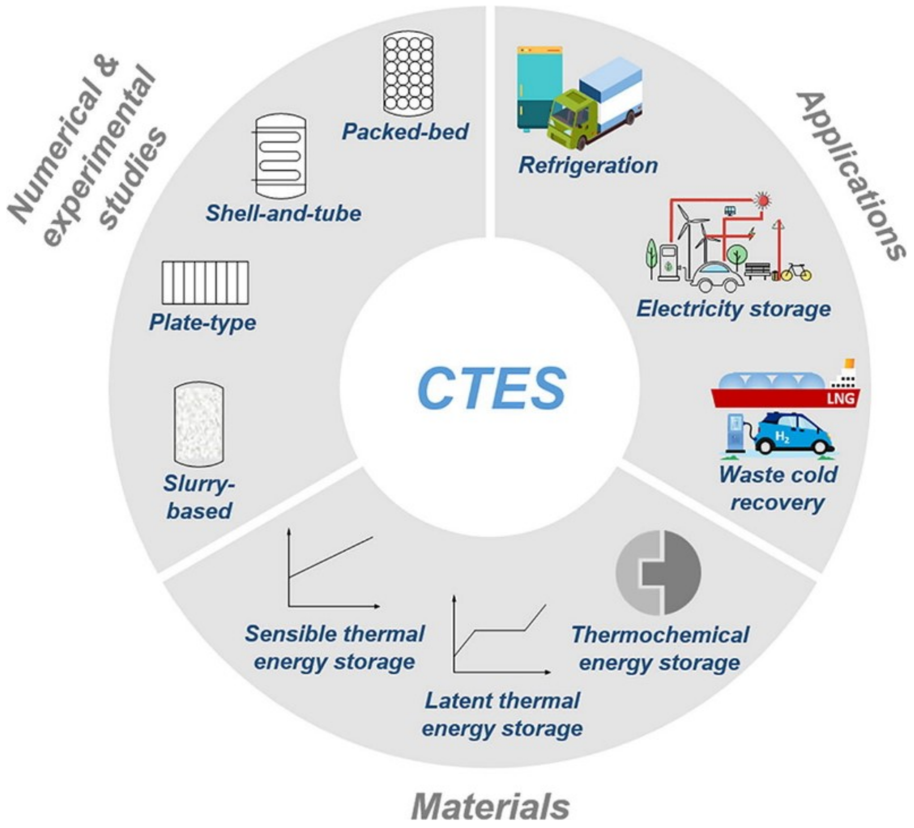


Figure 1.3: CTES materials, technologies, and applications reviewed in this thesis [7].

1.1.2.1 CTES materials

Like other thermal energy storage temperature ranges, CTES materials can also be classified into sensible, latent, and thermochemical materials.

Solid sensible materials, including rocks, concrete, ice, sodium chloride, granite, aluminum oxide, and plastic materials, are the most commonly used CTES material for extremely low-temperature applications. Liquid sensible materials, on the contrary, are not commercially deployed in the sub-zero temperature range due to a lack of proper material species. The number of species of existing or potential phase change materials (PCMs) mentioned in the literature is more than sensible materials. Pure substances, homogenous mixtures, nanoadditives, composite materials, and PCM slurries have been widely studied for sub-zero temperature applications. However, the thermal performances of the PCMs, especially the energy densities and thermal conductivities, drop dramatically as the phase change temperature decreases, making them not significantly more attractive than sensible materials in extremely cold temperatures. For thermochemical materials, the sorption cycle is the only type that has been widely studied. Besides ammonia/water, more working pairs of sorbents and refrigerants should be investigated.

1.1.2.2 CTES containment and heat transfer methods

Compared to CTES material studies, the number of numerical and experimental studies on CTES containment and heat transfer methods is still limited. However, most papers have been published in recent years, indicating a growing interest in this field.

Among the various containment and heat transfer methods, pack-bed using sensible materials or macroencapsulated PCMs is the most studied storage type. However, pack-beds suffer from significant pressure loss, large void volume, and high manufacturing cost for macroencapsulation that works in cryogenic temperatures. Shell-and-tube CTES is also commercially available. It has the lowest void fraction and highest energy density compared to other CTES types. But shell-and-tube CTES needs to overcome the problem of less heat transfer area. The development of plate-shaped CTES is at its early stage; its thermo-mechanical problems caused by the PCM's temperature and volume change should be properly handled. For the slurry type, the power consumption during slurry production should be reduced, and the storage system design should be improved.

In general, more numerical and experimental studies need to be carried out to develop new designs of CTES units. Since the energy density and thermal conductivity of latent CTES materials decrease with the operating temperature, advanced methods need to be developed to improve the thermo-mechanical design, reduce the void volume, and enhance the heat transfer of the CTES units using these materials. A comprehensive designing tool of CTES units can be developed to maximize the thermal performance and minimize the cost.

1.1.2.3 Application of CTES in LNG-based energy systems

Various CTES systems have been installed for refrigeration, electricity storage, and waste cold energy recovery purposes. However, only a limited number of studies mentioned using CTES for LNG cold energy harvest and utilization [17], and few CTES storage units have been comprehensively designed or built for LNG energy systems. So far, only one large-scale CTES unit (Senboku Terminal II of Osaka Gas) has been commercially deployed in LNG energy systems to recover the LNG cold energy for boil-off gas reliquefication during the nighttime [24–28]. Moreover, the benefits of CTES in enhancing the energetic and economic performances of LNG energy systems are rarely assessed. Especially, limited research quantitatively discussed the role of CTES in helping effectively utilize the LNG cold energy by smoothing the daily and seasonal LNG supply fluctuation due to varying electricity and city gas demand [29].

Hence, despite the vast potential, using CTES for LNG-based energy systems is far from thoroughly studied. Research topics such as the improvements in better designing and using CTES for LNG cold energy utilization, assessment of the role of CTES in LNG energy systems, and using LNG cold energy for more applications with the help of CTES, are worth investigating.

	Research stages	Potential research opportunities
Materials		
Sensible materials (solids)	Commercially available	Explore local or recyclable materials.
Sensible materials (liquids)	Some candidate materials selected but have not been widely applied	Search for more materials for lower temperatures. Resolve the health, safety and corrosion issues.
Pure substance PCMs	Commercially available	Increase the energy densities and heat conductivities. Resolve the health, safety and corrosion issues for some materials.
Homogeneous mixture PCMs	Many eutectic solutions are commercially available	Decrease the phase change temperature. Improve the thermal properties, suppress the subcooling, reduce phase separation.
Nanoadditive and composite PCMs	Additives for salt mixture and paraffins available, more under development	Explore more additives and matrixes. Evaluate the long-term performance. Understand the inherent mechanism.
Microencapsulation and other slurry PCMs	Ice slurry and some microencapsulation commercially available.	Reduce the production cost, improve the mechanical stability of the capsules, understand the basic physical properties.
Thermochemical materials	Ammonia absorption commercially available, other types in early stages	Explore more working pairs and reactions. Resolve the health, safety, and corrosion issues for some materials.
Numerical & experimental studies		
Shell-and-tube	Only heat transfer related simulation, limited experimental studies	Improve heat transfer. Explore new materials. Conduct thermo-mechanical simulation.
Packed-bed and thermocline	1D simulations based on simple codes, packed-bed with sensible filler available.	More studies on simulation and experimentation of liquid thermocline. Reduce the cost of macroencapsulation.
Slurry-based	Simulation and experimentation for slurry generation process	More numerical and experimental studies for system design, slurry generation, heat transfer, and fluid dynamics properties.
Plate-shaped	1D simulations and early stage containment studies, macroencapsulation available	Improve the heat transfer and increase mechanical flexibility. Conduct thermo-mechanical studies.
Applications		
Electricity storage (LAES, PTES, SFES)	LAES commercially available, PTES and SFES prototyping	Improve the CTES system design. Explore new applications and new materials.
Waste cold recovery (LNG, H_2)	One LNG project commercially deployed, more under development	Identify more waste cold sources and improve the CTES system design.
Refrigeration (active, passive)	Small-scale units commercially available, large-scale have not been widely applied	Explore more large-scale applications and grid integration of renewable energies.

Figure 1.4: Development stages and research directions of CTES in sub-zero temperature ranges [7].

1.2 Paper 1: A comprehensive review on sub-zero temperature cold thermal energy storage materials, technologies, and applications: State of the art and recent developments

1.2.1 Overview

Cooling and refrigeration account for 25–30% of the global electricity consumption, and this consumption is expected to surge 33-fold by 2100. Meanwhile, despite the massive amount of energy dedicated to producing cold energy, various cold sources are not efficiently utilized or even generally wasted. The fast-growing demand and production of cold energy, along with the newly trending concept of “cold economy,” triggered the urgent need to develop advanced CTES technologies to recover the waste cold energy, enhance the performance of refrigeration systems, and improve renewable energy integration.

This study provides a systematic and comprehensive review of a wide range of existing and potential CTES materials, technologies, and applications at sub-zero temperatures (from around −270 °C to below 0 °C). By identifying the research gaps where further efforts are needed, the review outlines the potential development directions of the next generation CTES technologies. Moreover, this study also outlines the selection criteria for suitable materials and storage types for each application.

1.2.2 Contribution to the state-of-the-art

The study found that the vast potential of CTES is far from being fully deployed. For CTES technology materials, more existing or potential PCMs are mentioned in the literature than sensible materials. However, fewer PCMs are available below -50°C, and their latent heat drops dramatically as the phase change temperature decreases. The most proposed or used storage types for sub-zero cold thermal energy storage are pack-bed, thermocline, shell-and-tube, plate-shaped, and slurry-based. Although some storage units are commercially deployed, more numerical and experimental studies should be carried out to enhance the performance of these storage units, especially improving the thermo-mechanical design and enhancing the heat transfer. Although some CTES systems have been proposed or installed in refrigeration systems (both active and passive), electricity storage systems (liquid air energy storage, pumped thermal energy storage, and superconducting flywheel energy storage), and waste cold energy recovery systems (regasification process of liquified natural gas and hydrogen), its potential is not fully unveiled. Improvements of better using CTES in such applications, as well as research efforts to explore more applications, are needed.

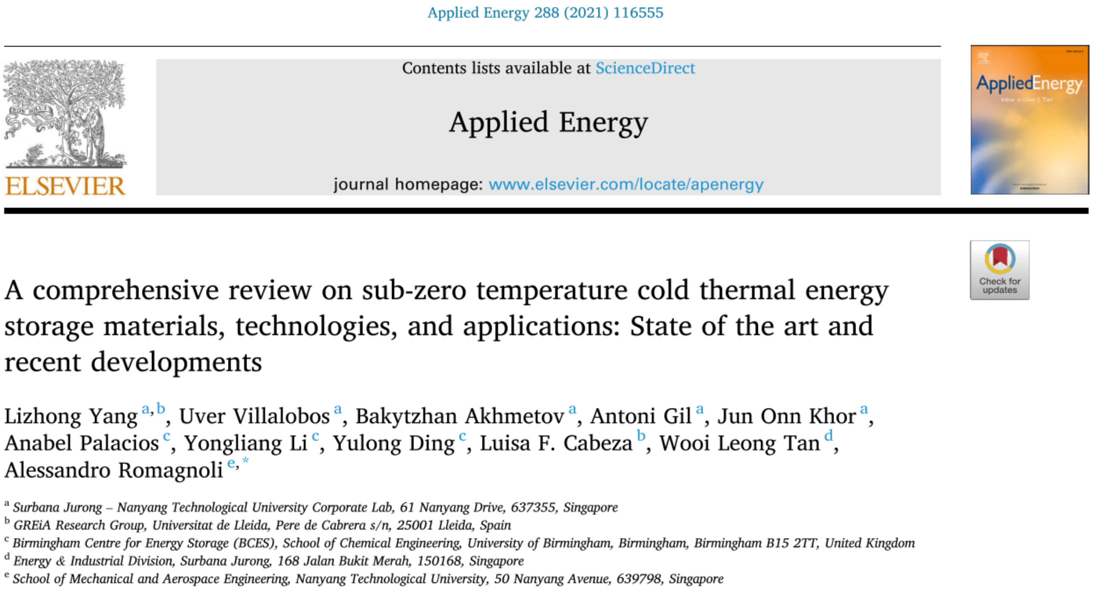
1.2.3 Contribution of the candidate

The candidate proposed and conceived the structure of the paper, conducted the review of the experimental studies and applications. The candidate also contributed to the CTES material and conclusion parts.

1.2.4 Journal paper

The scientific contribution from this research work was published in Applied Energy in 2021.

Reference: Yang L, Villalobos U, Akhmetov B, Gil A, Onn J, Palacios A, et al. A comprehensive review on sub-zero temperature cold thermal energy storage materials, technologies, and applications: State of the art and recent developments. Appl Energy 2021;288:116555. https://doi.org/10.1016/j.apenergy.2021.116555.



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A comprehensive review on sub-zero temperature cold thermal energy storage materials, technologies, and applications: State of the art and recent developments

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1.3 Objectives

From the literature review, we realized the dearth of comprehensively designed and built CTES units for LNG cold energy harvest and utilization. We have also identified the lack of quantitative analysis of the role of CTES in such energy systems. Therefore, the main goal of this thesis is to investigate the proper design of CTES units used for LNG energy systems, evaluate the impacts of CTES on the system performance, and explore the methods for heat transfer enhancement of the CTES units.

This thesis mainly focuses on using latent heat CTES materials, or PCMs, to capture and store the LNG cold energy due to their high energy density and chemical stability. Since the PCMs' heat of fusion and thermal conductivities decrease with the temperature, special attention needs to be paid when designing the CTES units, including proper selection of the CTES materials, reduction of the void volumes to increase the energy density from the unit level, and enhance the heat transfer inside the CTES units.

These goals led to the main research activities of this thesis, including:

- Development of a comprehensive CTES design method including storage material selection and geometry optimization
    - Identify the steps to follow of designing a CTES unit and the proper optimization algorithms for each step
    - Automate the whole design process of material-geometry optimization
- Application of the CTES design method to an LNG energy system
    - Design and optimize an LNG energy system and the corresponding CTES units
    - Quantify the contribution of the CTES to the LNG energy system's operating performance when subjected to LNG supply fluctuation
- Development of a CTES heat transfer enhancement technique
    - Develop a numerical, experimental, and optimization algorithm-based methodology to measure the effective thermal conductivity of heat transfer enhancement techniques in CTES modules
    - Develop a new design of heat transfer enhancement technique and measure its effective thermal conductivity

1.4 PhD Thesis structure

This thesis consists of five chapters (as shown in the scheme of the structure of the PhD study presented in Figure 1.5). Chapter 1 starts with an introduction to the mismatch between cold energy demand and supply, the potential role of CTES in an LNG-based cold economy, and the state-of-the-art of CTES studies through Paper 1. The objectives of the thesis, including developing a CTES design method, applying the method, and developing a heat transfer enhancement technique, are also introduced. To fulfill the objectives, Chapter 2 describes the methodologies of the studies conducted in this thesis, including the numerical methods adopted, thermodynamic models developed, optimization algorithms used, and experimental setup designed. Chapter 3 covers the overviews, contributions to state-of-the-art, and contributions of the candidate of Paper 2, 3, and 4. Chapter 4 discusses the results obtained in the papers, including the performance of the CTES design method, benefits of the CTES designed to an LNG energy system, the development and the effective thermal conductivity measurements of a heat transfer enhancement technique. Finally, Chapter 5 states the global conclusions of the thesis and proposes the future work following this thesis.

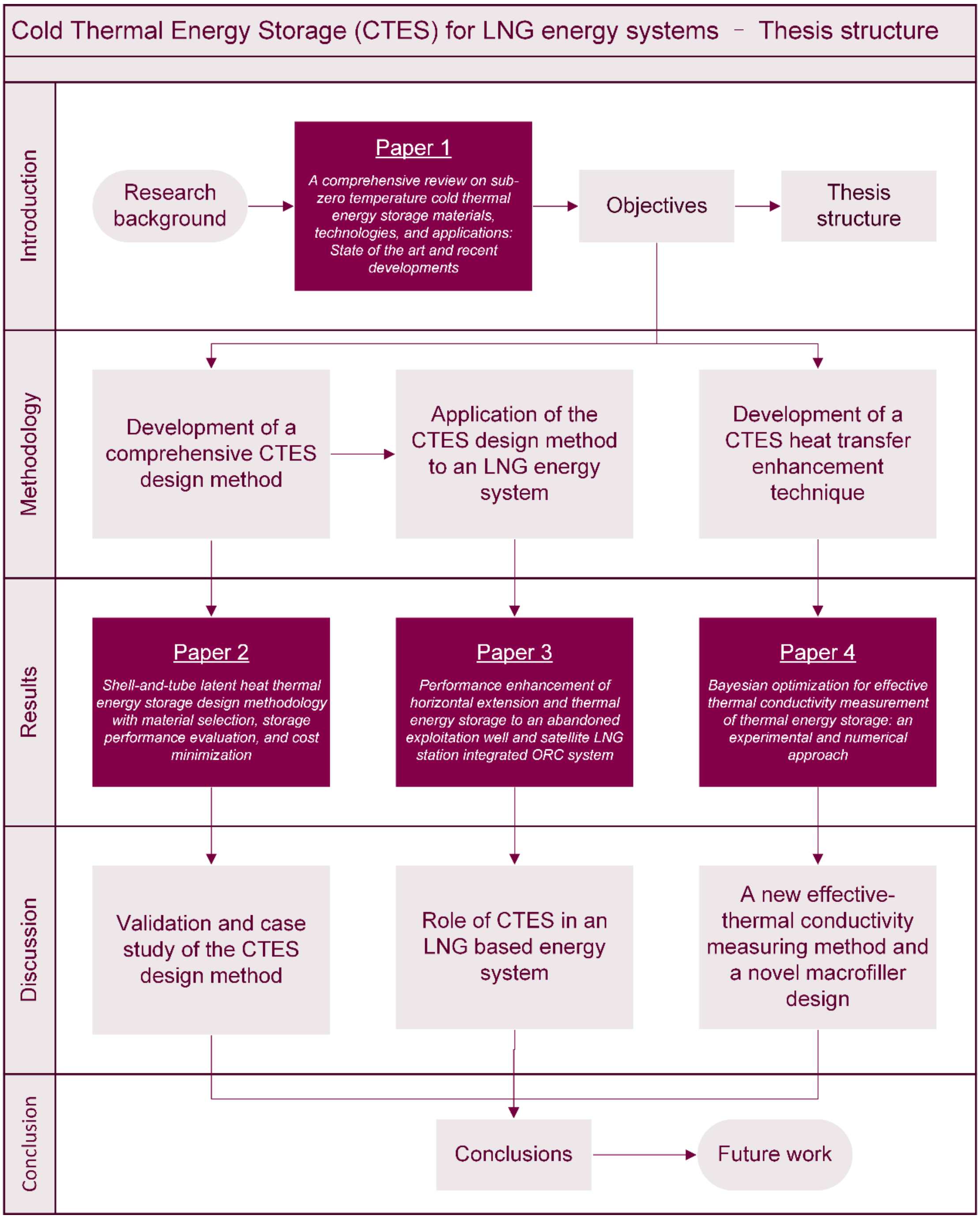


Figure 1.5: Scheme of the PhD thesis structure

2 METHODOLOGY

As introduced in Section 1.4, this thesis aims to develop a proper design tool of CTES units, apply the tool to LNG energy systems, and explore heat transfer enhancement methods of CTES units. Therefore, the thesis mainly consists of three parts: 1) development of a comprehensive CTES design method including storage material selection and geometry optimization, 2) application of the CTES design method to an LNG energy system, and 3) development of a new heat transfer enhancement technique and measure its effective thermal conductivity. In this PhD thesis, computational and experimental methods are both used to fulfill the objectives. Optimization algorithms and energy system simulation techniques are also employed to facilitate the CTES design.

Designing a CTES unit is a complex procedure that involves a series of steps, mainly including the storage material selection, geometry optimization, and cost minimization. For each step, a comprehensive design method should automatically process a broad range of materials with detailed property data, quickly obtain reliable simulation results with limited computing resources, and assess the cost of the CTES for specific energy systems. From the literature review, we discovered that limited studies covered all of these parts. In Paper 2, we proposed a comprehensive and automatic CTES design method for shell-and-tube units using PCMs.

As illustrated in Figure 2.1, the method consists of two parts, the material assessment and the geometry assessment.

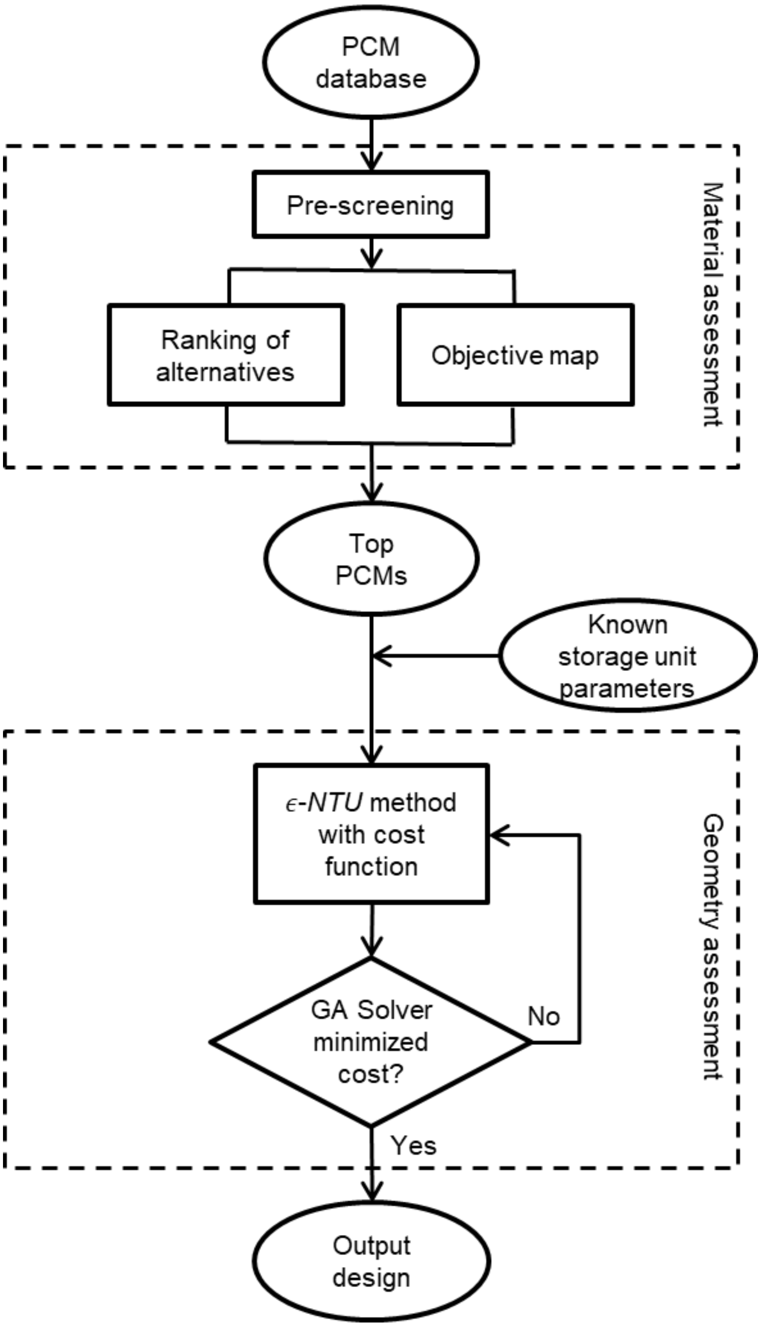


Figure 2.1: The workflow of the comprehensive CTES design method [30]

For the material assessment, a multi-criteria material assessment methodology is developed based on our prior studies [31,32]. The methodology first prescreens a PCM database and selects some PCMs based on the goals and scopes of the energy system, then uses multi-attribute decision making (MADM) ranking and multiple objective decision making (MODM) examinations methods to select out the final results. For the geometry assessment, the ε-NTU method developed by Tay et al. [33] is used to simulate the average charging and discharging power of the CTES unit. The f.o.b. cost of a shell-and-tube TES unit is assumed to contain two parts, the PCM cost, and the containment cost. For the containment cost, we assumed that it is equal to a shell-and-tube heat exchanger of the same geometry. In the last step, the Genetic Algorithm (GA) [34] is adopted to optimize the geometry design that minimizes the overall f.o.b. cost of the CTES unit. The design method is demonstrated by searching for the optimized geometry design of TES units in the context of energy systems in Paper 2 and 3.

Parametric analysis was conducted to reveal the influence of different shell and tube materials on the overall f.o.b. cost of a TES unit working with a solar absorption chiller system in Paper 2. The CTES designed method is also applied in an LNG energy system in Paper 3 to design the CTES modules for an abandoned exploitation well and satellite LNG station integrated organic Rankine cycle (ORC) system. In this system, a two-stage ORC was selected to convert the geothermal energy from the abandoned exploitation wells (AEWs) and waste cold energy from satellite LNG stations to electricity. CTES is used to maximize the cold energy harvested from the highly fluctuating LNG supply profile and, therefore, smooth the electricity output profile. Hence, this study mainly contains three parts: 1) design of the LNG energy system, 2) design of the CTES in the system, and 3) comparison of the system performance with and without CTES.

For the LNG-based energy system design, a CFD model was developed and validated for the borehole heat exchangers to extract the geothermal energy from the AEWs. Parametric analysis was conducted to understand the influence of temperature gradient, HTF flow rate, well depth, and length of the horizontal parts to the outlet temperature. The two-stage ORC was modeled and validated using a first law of thermodynamics model. Efficiency degradation of pumps and turbines, when subjected to highly fluctuating LNG flowrates, is evaluated using experimentally measured performance curves. Bayesian optimization using Gaussian process [35] is employed to be the optimization algorithm to search for the best ORC parameters, including the working fluid flow rate, operating pressures and temperatures. For the CTES design, the design method developed in Paper 2 was adopted.

The ORC performance comparison process with and without the CTES modules is illustrated in Figure 2.2.

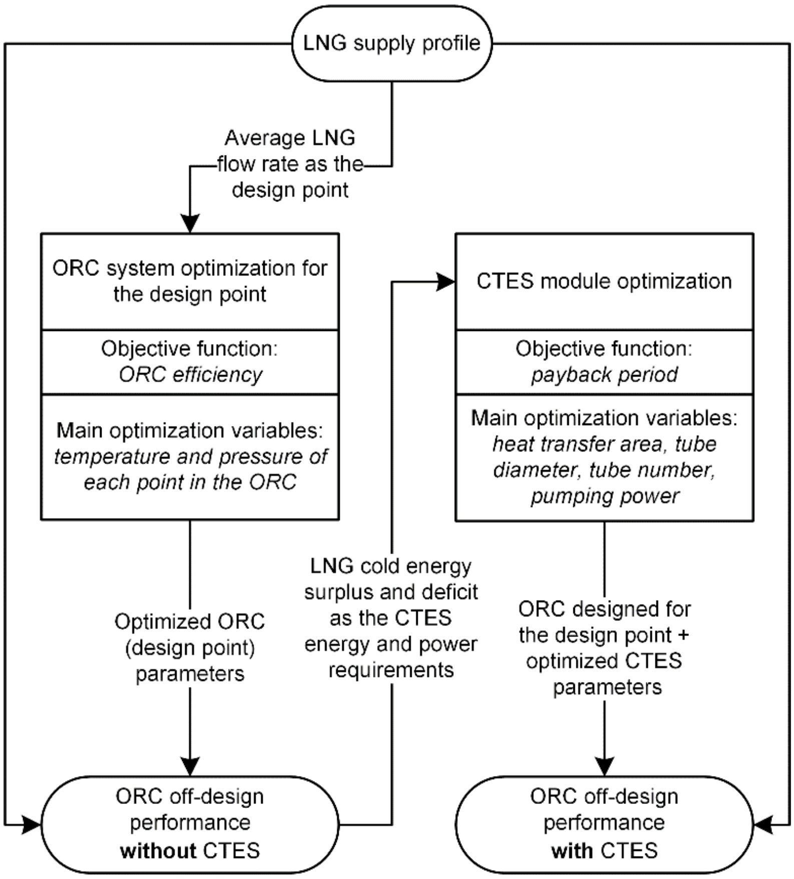
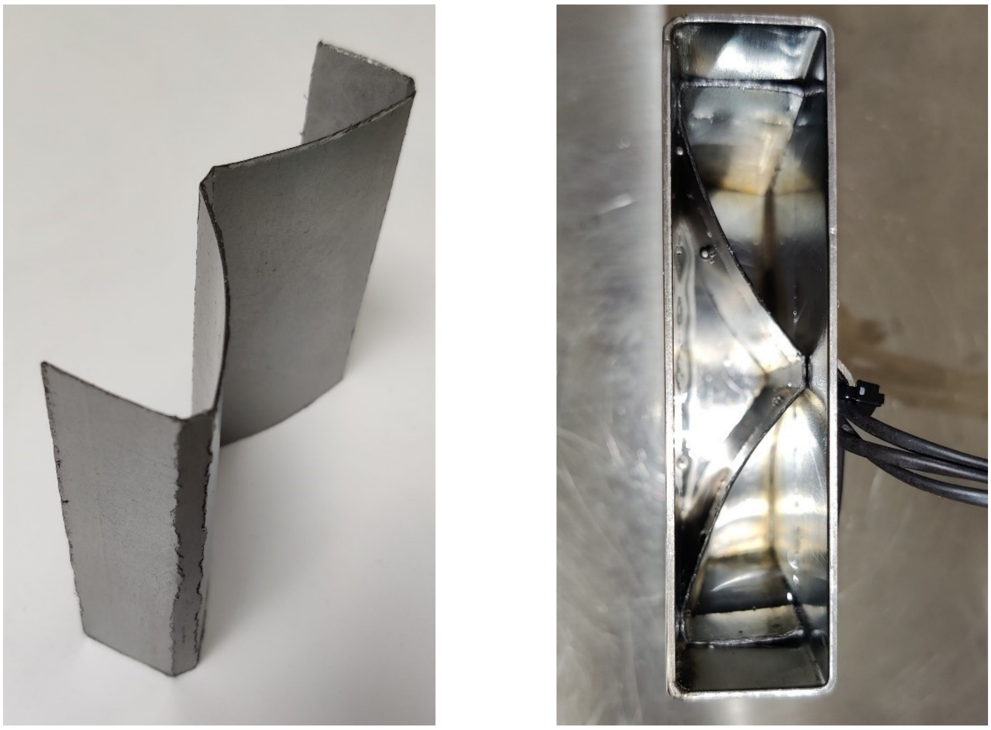


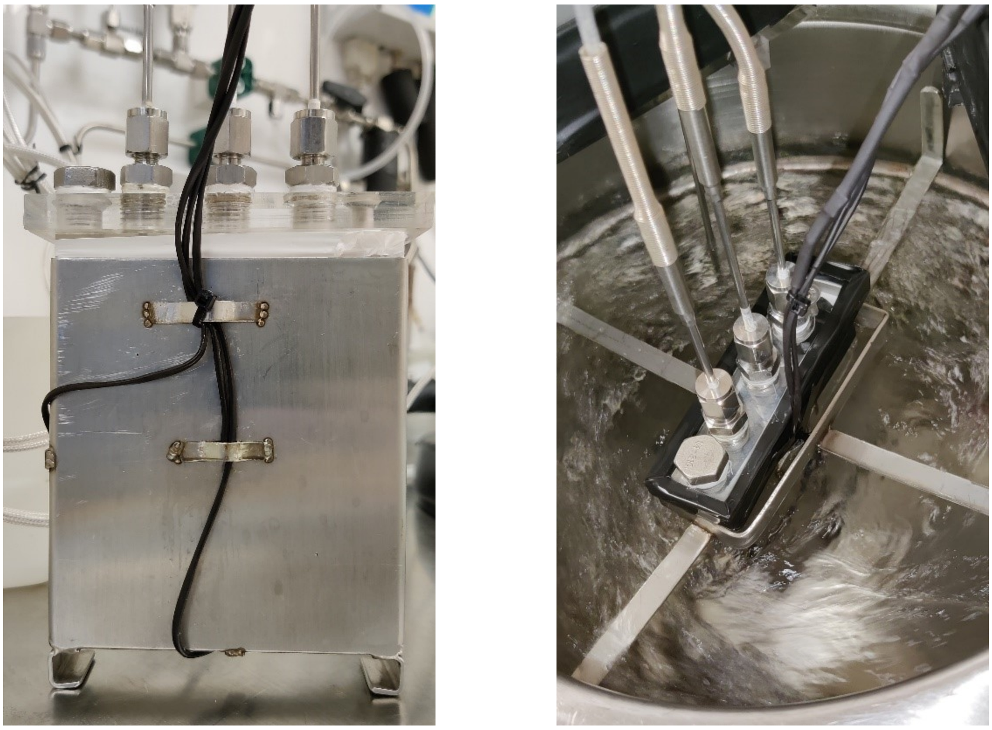
Figure 2.2: Method to compare the performance of the ORCs with and without the CTES [49]

The average LNG flow rate was selected as the design point of the ORC system. The LNG cold energy of the design point is then used as the input parameters to the CTES design. The Gulf Gas Mixture (NIST1) composition [36] composed of ten compounds was taken as the LNG composition to evaluate the cold energy extracted from the LNG under various pressures. The overall efficiencies and net electricity production of the ORC system with and without the CTES were compared when subjected to a typical 24-hour fluctuating LNG profile.

In addition to the CTES design method and its application, from the literature review in Paper 1, we identified heat transfer enhancement as a critical research topic to improve CTES design and a key direction for CTES studies. This thesis studied a novel macrofiller design to enhance the effective thermal conductivity and suppress the subcooling in Paper 4. The macrofiller is fabricated from a graphite sheet (Figure 2.3a). A dual-arch shaped design was adopted to ensure good thermal contact with the CTES container walls when subjected to the volume change of the PCM during phase transitions.



(a) (b)



(c) (d)

Figure 2.3: Experimental setup for the effective thermal conductivity measurement of the graphite sheet-based macrofiller to enhance the heat transfer of the PCM. (a) The design of the dual-arch shaped graphite sheet macrofiller; (b) PCM and macrofiller in a test cell with the same thickness of a plate-type CTES unit in the real applications; (c) the test cell with the resistance temperature detectors inserted; (d) sealed test cell in a thermal bath.

The macrofiller is then inserted into a test cell that has the same thickness as a plate-type CTES module (Figure 2.3b and c). A thermal bath (Figure 2.3d) provides accurately controlled temperature conditions for the PCMs inside the test cell. The temperature profiles of various locations in the test cell are measured by resistance temperature detectors.

Using the temperature profiles, a numerical and machine learning optimization algorithm-based method is developed in Paper 4 to measure the effective thermal conductivity (k_{eff}) of the samples inside the test cell assembly. As illustrated in Figure 2.4, the method contains three parts: 1) experimental measurement, 2) a 3D CFD model, and 3) a k_{eff} updating model.

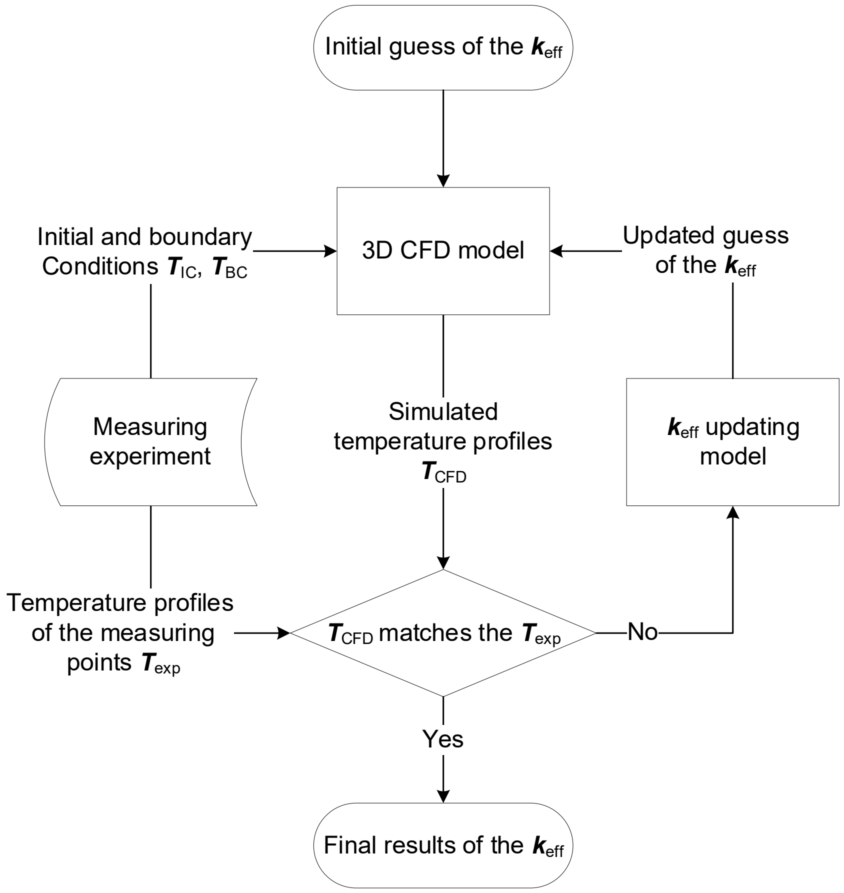


Figure 2.4: Method to compare the performance of the ORCs with and without the CTES [50]

The 3D CFD model is a finite volume method (FVM) heat conduction model for the test cell developed in C++. The k_{eff} updating model is a Bayesian optimization model using Gaussian process [35], which is an optimization algorithm based on machine learning (also used in Paper 3) to determine the best performing ORC system parameters. With the initially guessed k_{eff} values, the 3D CFD model simulates the temperature profiles of the test cell using the experimentally measured boundary conditions. The k_{eff} updating model developed in Python generates new k_{eff} values based on the comparison between the experimentally measured temperature profile $\boldsymbol{T}_{exp}$ and $\boldsymbol{T}_{CFD}$ generated by the 3D CFD model. After a series of iterations, the accurate k_{eff} values can be obtained. The method was validated using COMSOL simulations.

3 RESULTS

Paper 2, 3, and 4 that comprise this PhD are introduced in this chapter. Each paper is dedicated to one primary objective of the PhD thesis, including 1) investigating the proper design of CTES units used for LNG energy systems, 2) evaluating the impacts of CTES on LNG energy systems performance, and 3) exploring the methods for heat transfer enhancement of the CTES units, as discussed in Section 1.4.

3.1 Paper 2: Shell-and-Tube Latent Heat Thermal Energy Storage Design Methodology with Material Selection, Storage Performance Evaluation, and Cost Minimization

3.1.1 Overview

Latent heat thermal energy storage (LHTES) units have the advantage of storing and releasing thermal energy at a nearly constant temperature, high energy density, and high chemical stability [37,38], making it a good fit for temperature management services [39,40]. Shell-and-tube is a widely used LHTES type that delivers high heat transfer effectiveness, high charging/discharging power, high energy density, low cost, and low-pressure drop [41,42]. LHTES using shell-and-tube can be used in a wide range of applications, including active and passive refrigeration, waste cold recovery, and electricity storage [7].

However, although shell-and-tube LHTES is widely studied [43], limited research has been dedicated to storage unit design methodology. Comprehensively designing a shell-and-tube LHTES involves several steps, including storage material selection based on the parameters, simulation of the storage unit, and cost minimization. Previous studies focused on shell-and-tube LHTES designing suffer from the significant amount of effort to choose the best materials, time-consuming computational fluid dynamics simulations, or lack of flexibility when selecting the designing parameters.

This study proposed a comprehensive, automatic, and fast methodology that includes material assessment and geometry optimization. Multi-attribute decision-making and multi-objective decision-making tools are used to select the most appropriate material candidates from a large database. ε-NTU method is adopted to quickly simulate the LHTES performance with high flexibility. Cost reduction is used to optimize all the parameters and generate the best LHTES design.

The method is validated against experimental results in the literature, and a case study is conducted to demonstrate the method by designing an LHTES unit for solar absorption chiller application.

3.1.2 Contribution to the state-of-the-art

The study presented the first of the kind comprehensive shell-and-tube LHTES designing tool that automated the whole designing process from material selection to cost minimization. The two-step material selection method can deal with a large material database and consider various parameters, while the simulation offers a quick yet accurate estimation of the performance of the storage unit.

Therefore, the methodology proves to be an efficient, reliable, and systematic tool to fulfill the research gap of a fast and accurate comprehensive design of shell-and-tube LHTES. The designer a of shell-and-tube LHTES unit can use this methodology to conduct the preliminary design instead of directly running time-consuming CFD analysis or costly experimental studies.

Moreover, besides shell-and-tube LHTES, similar methodologies following the same concept can also be developed for other storage types and materials.

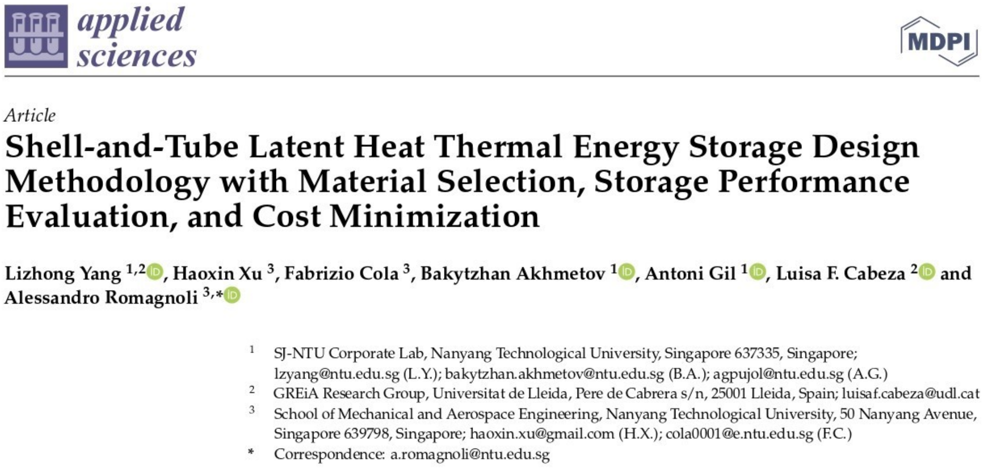
3.1.3 Contribution of the candidate

The candidate improved the design methodology, conducted the method validation, and analyzed the results for the design method. The candidate also participated in the conceptualization of the design method.

3.1.4 Journal paper

The scientific contribution from this research work was published in Applied Sciences in 2021.

Reference: Yang L, Xu H, Cola F, Akhmetov B, Gil A, Cabeza LF, et al. Shell-and-Tube Latent Heat Thermal Energy Storage Design Methodology with Material Selection, Storage Performance Evaluation, and Cost Minimization. Appl Sci 2021;11. https://doi.org/10.3390/app11094180.



applied sciences

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Article

Shell-and-Tube Latent Heat Thermal Energy Storage Design Methodology with Material Selection, Storage Performance Evaluation, and Cost Minimization

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3.2 Paper 3: Performance enhancement of horizontal extension and thermal energy storage to an abandoned exploitation well and satellite LNG station integrated ORC system

3.2.1 Overview

When the service of an oil or gas exploitation well ends, it will be discarded and become an abandoned exploitation well (AEW). Tens of millions of AEWs can be found worldwide, with some close to populated areas and posing threats to the surrounding environments [44]. On the other hand, around half of the cost of developing a geothermal plant can be attributed to drilling [45]. If the AEWs can be converted to borehole heat exchangers, the high investment of AEW decommissioning and geothermal plants drilling can be significantly avoided. However, a major drawback of AEW geothermal extraction is that the temperature is usually less than 150°C, making power generation cycles utilizing the AEW geothermal energy suffer from low efficiencies, even as low as around 5% [46].

One viable solution is to connect the AEW to a satellite LNG station. The usually wasted LNG cold energy can hence serve as the cold source of the power cycle to increase the system efficiency. However, the LNG supply profile of a satellite LNG station suffers from high fluctuation according to the volatile natural gas demand. Therefore, CTES can be introduced to shift the peak and smooth the LNG cold energy supply.

In this study, we proposed and designed a novel abandoned exploitation well and satellite LNG station integrated ORC system energy system using CTES. The LNG cold energy can increase the ORC efficiency to above 20%. A modular CTES unit is designed according to the requirements of the energy system using the method developed in Paper 2. The role of CTES in such a system is then assessed. The integrated energy system is subjected to the highly unstable LNG cold energy profile during off-design operation. Compared to the ORC design without the CTES, the ORC with CTES can produce 25% more net electricity. Therefore, CTES made the integrated energy system of AEW and satellite LNG stations a viable solution for future AEW revitalization and LNG cold utilization.

3.2.2 Contribution to the state-of-the-art

The study proposed for the first time the concept of combining LNG cold energy to utilize the low-grade heat from AEW and generate electricity with high efficiency. To increase the recovered temperature from the AEW, horizontal extension in the AEW is considered in the model.

The CTES design method developed in Paper 2 is applied to design the CTES models in the integrated ORC-geothermal-LNG power generation system. The benefits of the

CTES modules are quantified to demonstrate how CTES can increase the off-design system efficiency and power production.

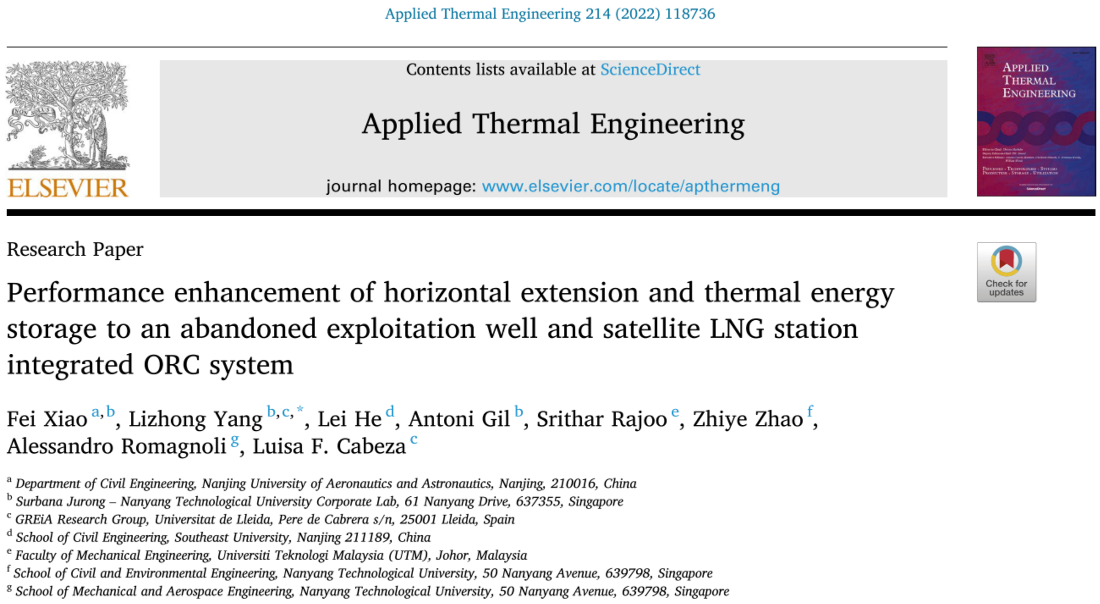
3.2.3 Contribution of the candidate

The candidate participated in the conceptualization of the ORC-geothermal-LNG power generation system. The candidate also designed and optimized the system together with the CTES modules, assessed the role of CTES in the system, and assisted in the validation of the borehole heat exchanger model.

3.2.4 Journal paper

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

Reference: Xiao F, Yang L, He L, Gil A, Rajoo S, Zhao Z, et al. Performance enhancement of horizontal extension and thermal energy storage to an abandoned exploitation well and satellite LNG station integrated ORC system. Appl Therm Eng 2022;214:118736. https://doi.org/10.1016/j.applthermaleng.2022.118736.



Applied Thermal Engineering 214 (2022) 118736

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Research Paper

Performance enhancement of horizontal extension and thermal energy storage to an abandoned exploitation well and satellite LNG station integrated ORC system

Fei Xiao [a,b], Lizhong Yang [b,c,*], Lei He [d], Antoni Gil [b], Srithar Rajoo [e], Zhiye Zhao [f], Alessandro Romagnoli [g], Luisa F. Cabeza [c]

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3.3 Paper 4: Bayesian optimization for effective thermal conductivity measurement of thermal energy storage: an experimental and numerical approach

3.3.1 Overview

TES heat transfer enhancement techniques commonly include adding microfillers or macrofillers to the TES materials or enclosures. Compared to the former, inserting macrofillers is easy to manufacture, does not have precipitation problems, and can be engineered to reduce the thermal contact resistance. However, the heterogeneous nature of macrofillers makes it challenging to measure the effective thermal conductivity (k_{eff}) of the TES enclosure as a whole by directly using material-level instruments or methods for homogeneous and isotropic media.

Therefore, this study proposes a combined Bayesian optimization, experimental, and numerical method to measure the k_{eff} of macrofillers inserted into the CTES unit. A new macrofiller design is also developed and tested.

For the measuring method, a 3D numerical model is established to compare with the experimental results with k_{eff} the only unknown parameter. Bayesian optimization using Gaussian process is used to find out the most accurate k_{eff} values through iterations of numerical and experimental result comparison.

The measuring method was applied to a novel dual-arch shaped graphite sheet-based macrofiller design that was engineered to ensure good thermal contact between the filler and the enclosure walls. The macrofiller design significantly enhanced the heat transfer and phase change performances of the PCM.

3.3.2 Contribution to the state-of-the-art

This study proposed a novel numerical, experimental, and Bayesian optimization-based method for effective thermal conductivity k_{eff} measurement. The method can accurately and quickly obtain the k_{eff} values for PCMs with macrofillers, as well as other bulky and heterogeneous structures that cannot be considered as continuous media.

With the method, we revealed that k_{eff} should be considered in the simulation of both the liquid and solid phases of PCM. Studies considering only k_{eff} for the liquid phase and neglecting the solid phase can lead to significant error. Possible reasons why k_{eff} of solid PCMs can be decreased are also analyzed.

We demonstrated the method with a novel dual-arch shaped graphite sheet-based macrofiller design for heat transfer enhancement. As listed in Table 3.1, the design performed well by increasing the k_{eff} by around 20% and suppressing the subcooling simultaneously. Moreover, its scalable design makes this macrofiller possible to be applied to larger CTES units.

Table 3.1 Effective thermal conductivity values of the macrofiller and its improvements compared to the PCM without the macrofiller [*].

	Liquid k_{eff} and improvement [W m^{-1} K^{-1}] (%)	**Solid k_{eff} and improvement [W m^{-1} K^{-1}] (%)**
Solidification	1.35 (11.8%)	1.68 (21.1%)
Melting	1.57 (24.6%)	1.69 (14.1%)

3.3.3 Contribution of the candidate

The candidate conceptualized the measuring method, programmed the simulation and optimization tools of the measuring method. The candidate also developed the macrofiller design, participated in the experimental setup design and the algorithm selection.

3.3.4 Journal paper

The scientific contribution from this research work was published in the Journal of Energy Storage in 2022.

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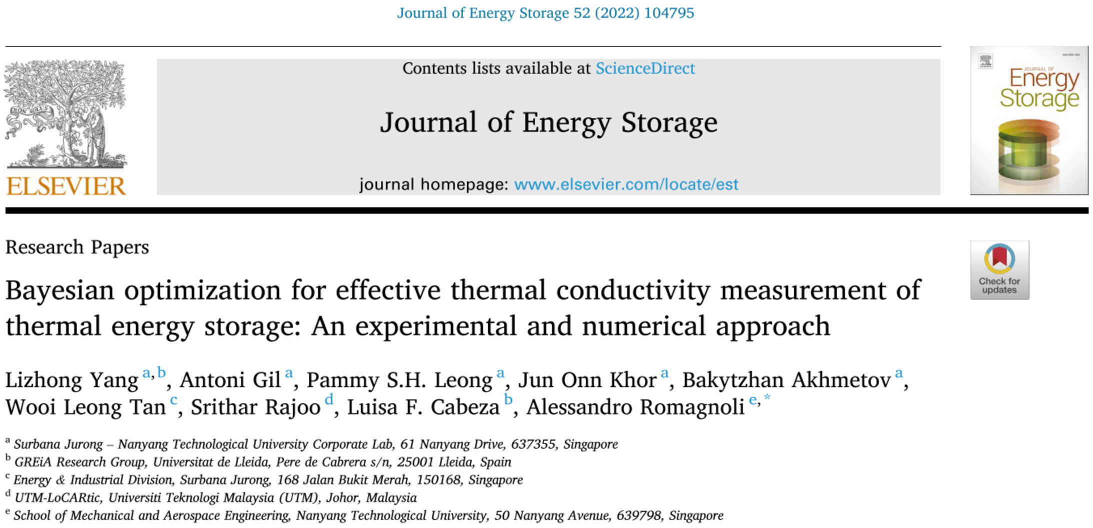
[*] Results of the table are taken from Paper 4 [50].

Reference: Yang L, Gil A, Leong PSH, Khor JO, Akhmetov B, Tan WL, et al. Bayesian optimization for effective thermal conductivity measurement of thermal energy storage: an experimental and numerical approach. J Energy Storage J 2022;52. https://doi.org/https://doi.org/10.1016/j.est.2022.104795.



Journal of Energy Storage 52 (2022) 104795

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Research Papers

Bayesian optimization for effective thermal conductivity measurement of thermal energy storage: An experimental and numerical approach

Lizhong Yang [a,b], Antoni Gil [a], Pammy S.H. Leong [a], Jun Onn Khor [a], Bakytzhan Akhmetov [a], Wooi Leong Tan [c], Srithar Rajoo [d], Luisa F. Cabeza [b], Alessandro Romagnoli [e,*]

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4 DISCUSSION

As stated in Chapter 1, this thesis focuses on designing and developing CTES technologies for LNG energy systems. To comprise this PhD study, Paper 1 reviewed the state of the art of the CTES studies; Paper 2 developed a CTES design method; Paper 3 applied the CTES design method, designed a new concept of LNG energy system to facilitate geothermal energy power production, and analyzed the role of the CTES units in such a system; Paper 4 designed a new type of macrofiller to enhance the heat transfer of the CTES, and developed a method to measure its effective thermal conductivity. The findings obtained from the four papers are discussed in this chapter.

Through the literature review, the research gaps of CTES technologies in sub-zero temperature ranges were identified. The thermophysical properties and performance enhancement methods of more than 200 existing and potential CTES materials were summarized. However, CTES materials suitable for cryogenic temperature applications are still scarce. Moreover, for PCMs, their thermophysical properties, especially the energy density and thermal conductivity, degrade as the phase change temperature decreases.

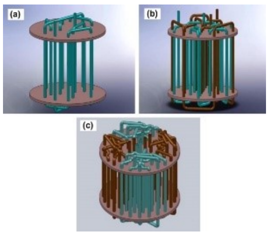
For the CTES containment and heat transfer methods, publications are still limited despite fast growth in recent years. Packed-bed and thermocline, shell-and-tube, plate-shaped, and slurry are the major types that have been built or proposed. For all the systems, there is a lack of comprehensive tools covering the entire designing process from material selection to storage unit geometry optimization. Moreover, due to the lower thermal conductivity of the CTES materials compared to high-temperature TES materials, proper heat transfer enhancement technique becomes more critical for CTES designs to be used in sub-zero temperature applications.

CTES has been applied in refrigeration systems, waste cold energy recovery, and electricity storage systems. However, more applications should be explored, especially for LNG cold energy recovery and utilization. Moreover, there is a lack of quantitative analysis of the role of CTES in such systems to enhance the system operation performance.

To address these research gaps, this PhD thesis first developed a comprehensive TES design method. The method automatically deals with all the design processes of a TES unit, including material selection, geometry optimization, and cost minimization. The method was validated through comparison with the results of three experimental studies in the literature. As shown in Table 4.1, the TES design method delivered high accuracy regardless of the TES unit configurations and operating conditions. The error was lower than 10% as long as the temperature difference between the fluids and the PCMs was less than 20 °C.

After the validation, the TES design method was used to design a TES unit in a solar thermal absorption chiller system. For a given set of design parameters, the f.o.b. costs of the CTES unit are mainly affected by the shell and tube materials. The cost of using carbon steel in both the shell and tubes was only 1/4 of using stainless steel. Therefore, if the PCM is not corrosive to the containment materials, the overall cost of the TES unit can be significantly reduced. On the other hand, if only considering reducing the f.o.b. cost from the material's perspective by using lower-cost yet more corrosive PCMs, the expensive containment materials may in the end lead to a higher overall cost.

Table 4.1 Average error of calculating the charging and discharging powers using the TES design method for three experimental studies in the literature [*]

Cases	**Gasia et al.** [47]	**Fadl & Eames** [48]	**Tay et al.** [33]
Configuration			
Number of tubes	49	1	1, 2, 4
Number of passes	2	55	14, 32, 64
Tube length	2.485 m	27 m	5.46, 11.62, 23.83 m
Tube inner & outert diameters	13.2, 17.2 mm	13, 15 mm	8, 10 mm [†]
Shell dimension	1273 (L) × 273 (H) × 527.5 mm (W)	520 (L) × 560 (H) × 160 mm (W)	290 (D) × 330 mm (H)
PCM	RT58	RT62HC	PCM0, PCM27
Melting temperature	53–59 °C	62–63 °C	0, 27 °C
HTF	Syltherm 800	Water	Aqueous based fluid
HTF and PCM temperature difference	~10 °C	~13 °C	~18 and 40 °C
HTF flow rate	500 kg h^{-1}	2–6 L min^{-1}	~ 0–0.07 kg s^{-1}
Flow scheme	Laminar	Turbulent	Laminar/turbulent
Average error	2.2%	8.5%	13% [‡]

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[*] Results of the table are adapted from Table 5 of Paper 2 [30].

[†] Calculated based on Table 1 in Castell et al. [51].

[‡] Calculated by Tay et al. [33] with high temperature difference (as high as 40 °C) between the HTF and the PCM.

In order to explore more applications of the CTES for LNG energy systems, an abandoned exploitation well and satellite LNG station integrated ORC system was designed based on the CTES design method. The recovered temperatures from the AEWs are usually less than 150°C, causing the ORC efficiency to be generally low if solely relying on the AEW geothermal energy. The cold energy from LNG satellite stations is hence a suitable cold sink for the ORC system. However, the LNG satellite stations suffer from highly fluctuating gas demands, significantly reducing the efficiency and overall power generation. For a typical LNG profile shown in Figure 4.1, the ORC system has to be cut off when the flow rate is too low and use only a fraction of the cold energy when the flow rate is too high. As a result, the ORC can only make use of 80.0% of the total LNG cold energy.

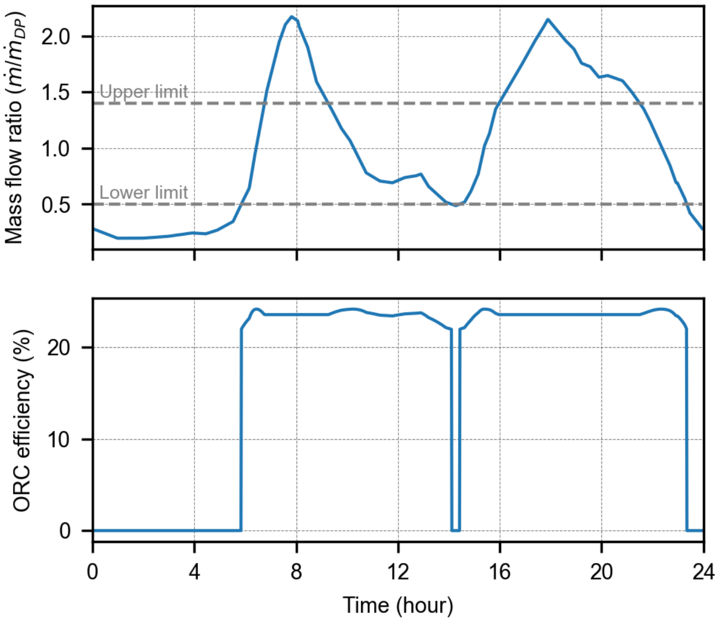

Figure 4.1: ORC efficiencies subjected to highly fluctuating LNG flow rates [49]

Therefore, CTES is used to store the surplus of the LNG cold energy and provide a constant cold energy supply to the ORC system. To maximize the flexibility of the CTES operation, 6 CTES units are used that can operate parallelly to cope with the varying LNG flow rate. As a result, 99.8% of the total cold energy available can be stored. Moreover, the cold energy supply from the CTES to the ORC is also more stable, resulting in an over 30% increase in the overall ORC efficiency and 25% increase in the net electricity production (as shown in Figure 4.2). Therefore, the contribution of CTES in an LNG energy system is quantified.

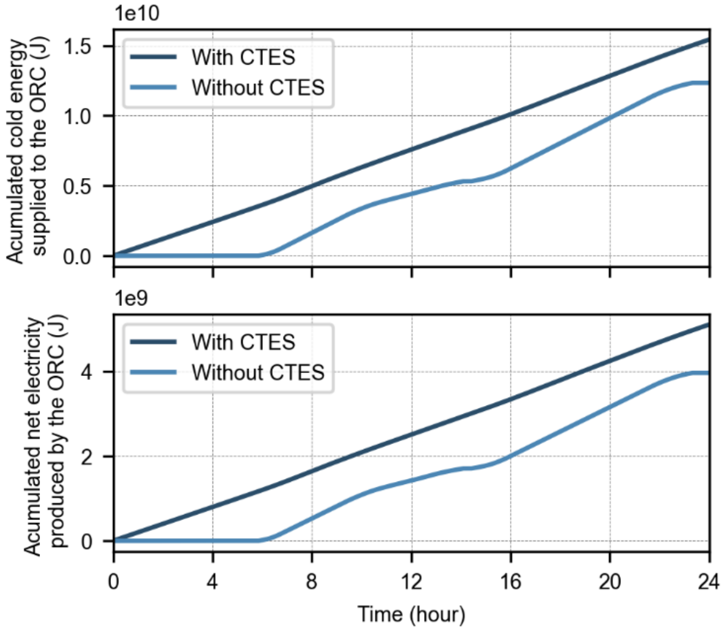

Figure 4.2: Accumulated LNG cold energy utilization and net electricity production with and without the CTES [49]

The next step of the PhD study then focused on designing a heat transfer enhancement technique for CTES units. To evaluate the performance of heat transfer enhancement techniques, effective thermal conductivity (k_{eff}) is a commonly used merit. However, existing measurement techniques for k_{eff} suffer from the problems of either inaccurate or slow measurements. As described in Chapter 2, this thesis developed a new method that combined experimental measurement, numerical simulation, and machine learning based-optimization algorithm to swiftly and accurately obtain the k_{eff} values. In the case of a PCM, with this method, the k_{eff} values of solid and liquid during melting and solidification can be obtained much faster and more accurately compared to the other methods. To validate the method, it is first used to measure the k_{eff} of de-ionized (DI) water as the PCM. With less than 20 calls, the method can achieve high accuracy results with the RMSEs (root-mean-square errors) of less than 2 K and R^2 above 0.98. A COMSOL model using the measured k_{eff} results showed good agreement with the experimental results, indicating that the k_{eff} measured by the method can be used in other CFD tools for accurate simulation and designing of TES units (as shown in Figure 4.3).

Moreover, the obtained k_{eff} values for the liquid and solid phases were around 1.2-1.3 W m^{-1} K^{-1} and 1.4-1.5 W m^{-1} K^{-1}. The liquid phase results agreed well with the results obtained in the other studies in the literature. Compared to the material heat conductivity of around 0.6 W m^{-1} K^{-1} (for liquid water), the increment is due to natural convection and unmelt PCM movement. The solid phase k_{eff} values, on the other hand, are rarely measured in the literature. Compared to the material heat conductivity of above 2.0 W m^{-1} K^{-1} (for ice), the decrease might be ascribed to two factors: 1) the contact thermal resistance between the ice and the walls as well as in the cracks between different layers of ice, 2) the air bubbles trapped in the ice structure due to the air cushion in the CTES containment. Therefore, for CTES simulations using the conduction models, non-negligible errors will occur if considering only the k_{eff} for the liquid phase but not the solid phase.

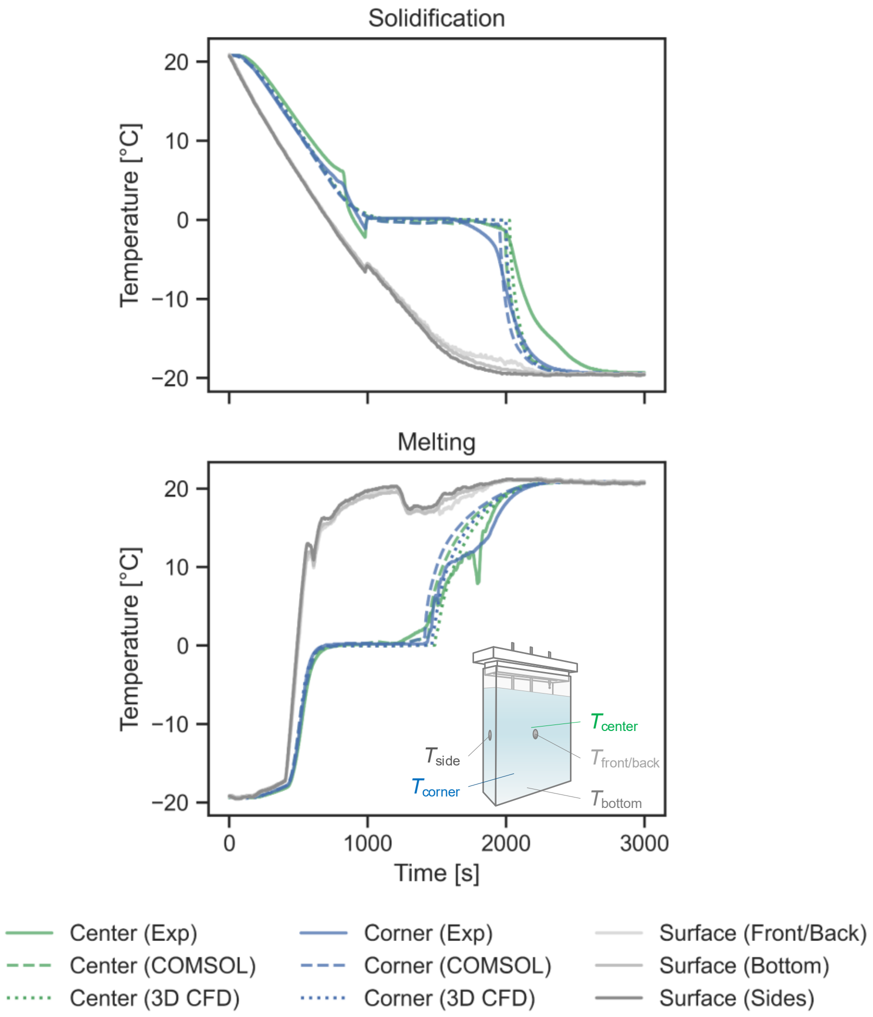

Figure 4.3: Temperature profiles of the experimental results and the 3D CFD & COMSOL models generated results using the k_{eff} values obtained [50]

The method is then used to measure the k_{eff} values of DI water with the graphite sheet-based macrofiller inserted. The average increase of the k_{eff} values was found to be around 20% (shown in Figure 4.4).

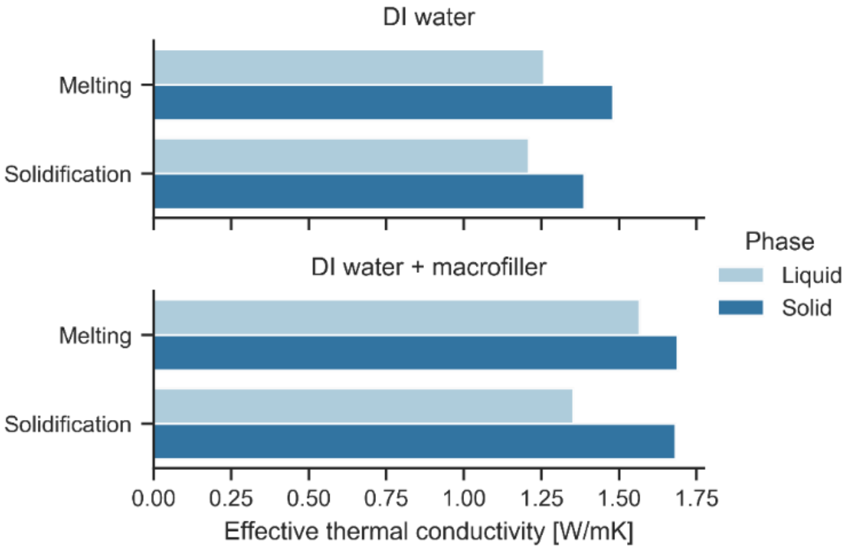

Figure 4.4: Measured k_{eff} values with and without the macrofiller for liquid and solid phases during melting and solidification processes [50]

Furthermore, no subcooling effect was observed during the solidification process, indicating that the porous structure of the macrofiller might have suppressed the subcooling. Further analysis found out that the macrofiller might have enhanced the CTES heat transfer in three ways: 1) increase the heat transfer area with a material of a higher thermal conductivity; 2) suppress the subcooling and, therefore, reduce the delay in the crystallization caused by the subcooling; 3) separating the unmelt PCM in the CTES units into several segments, hence increasing the solid PCM surface area due to smaller bulks. Therefore, the macrofiller design is a simple, low-cost, scalable, yet effective technique to enhance the heat transfer of CTES units.

Moreover, the study also revealed that k_{eff} is an ideal performance indicator of heat transfer enhancement techniques for CTES units. The reliability of some other indicators, such as the charging and discharging time, relies on strictly identical initial and boundary conditions during different experimental tests. k_{eff}, on the other hand, is less affected by the operating conditions. Therefore, it provides reliable comparisons without stringent experimental condition requirements.

5 CONCLUSIONS AND FUTURE WORK

5.1 Conclusions

This PhD study investigates the proper design of cold thermal energy storage (CTES) units, evaluates the impacts of CTES on LNG energy system performance, and explores the methods for heat transfer enhancement of the CTES units. Focusing on these objectives, the thesis conducted a comprehensive review of a broad range of CTES studies, developed a fast and accurate method of CTES design, applied the design method in LNG systems to understand the role of CTES in such systems, explored a heat transfer enhancement technique for CTES units, and developed a new method to measure its improvement to the effective thermal conductivity.

The thesis first reviewed around 250 studies about the materials, numerical and experimental studies, as well as the application of CTES technologies used in sub-zero temperature ranges (from -270 °C to 0 °C). The literature review found out that the vast potential of CTES is far from being fully unveiled, and a series of research directions were proposed. More CTES materials for applications below -50 °C should be developed with higher storage density and thermal conductivity. Numerical and experimental studies should focus more on heat transfer enhancement, thermo-mechanical property improvements, and system modular design. In addition, more applications should be explored with better CTES unit designs.

Based on these research directions, a comprehensive design method of shell-and-tube type TES for latent heat storage was developed. The method uses optimization algorithms and simulation methods to automatically carry out the whole TES design process from material selection to geometry optimization. With around 10 seconds, the method is able to generate a fast and reliable preliminary design of the TES units according to the requirements of the energy system.

The method was applied to design the TES units for a solar absorption chiller system and an abandoned exploitation well and satellite LNG station integrated ORC system. With the operating conditions fixed, shell and tube material selection was found to have the most significant impact on the TES f.o.b. cost. When subjected to highly fluctuating LNG flow rates, the CTES could maximize the utilization of the LNG cold energy, leading to a significant increase in the efficiency and net power generation of the ORC system (30% and 25%, respectively). CTES also has the capability to convert an LNG energy system to a virtual power plant.

For the heat transfer enhancement design of CTES unis, to test the effective thermal conductivity of bulky materials, an experimental, numerical, and machine learning-based optimization method was designed. The measuring method overcame the drawbacks of previous methods and proved to accurate and fast. A graphite sheet-based macrofiller was designed and tested. A dual-arch shaped design was made to improve the thermal contact between the filler and the container walls, as well as the other fillers. Using the above-mentioned measuring method, the macrofiller design increased the effective thermal conductivity by around 20% and successfully suppressed subcooling.

Therefore, this PhD thesis has broadened the knowledge about CTES used in LNG energy systems by developing a new design method for TES units, analyzing the role of CTES units in LNG energy systems, designing a simple yet effective heat transfer enhancement technique, and exploring a new method for effective thermal conductivity measurement.

5.2 Future work

While carrying out the research work of this PhD study, some more research topics arose but were not addressed in this thesis. Therefore, the recommendations for possible future work following this thesis are proposed in this section.

From the literature review, we found that the energy densities and thermal conductivities of PCMs decrease with the phase change temperatures. This thesis focused more on using better CTES unit design and heat transfer enhancement techniques to resolve these problems. Future work can also seek new CTES material formulas that have better thermo-physical properties while being nonflammable, non-toxic, and environmental friendly at the same time.

The TES design method proposed in this thesis involved only shell-and-tube TES using PCMs. Future studies can explore using the same design methodology for more CTES materials and storage types. The accuracy of the geometry simulation can also be further improved by considering natural convection.

This thesis proposed a macrofiller design for plate-shaped CTES to enhance the unit’s heat transfer. More macrofiller designs can be developed for both plate-shaped CTES and other storage types. Future studies can also apply this thesis's effective thermal conductivity measurement method to other storage types. Moreover, the factors that impact the effective thermal conductivity of CTES units using PCMs and fillers, including subcooling, thermal contact resistance, natural convection, unmelt PCM movements, and air bubble formation, are worth more investigation quantifying their effects on the heat transfer within the CTES unit.

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