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Sizing the Thermal Energy Storage Device Utilizing Phase Change Material (PCM) for Low-Temperature Organic Rankine Cycle Systems Employing Selected Hydrocarbons

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Abstract: Thermal energy storage (TES) looks to be a promising technology for recovering waste heat or other intermittent heat sources, especially if it is coupled with the organic Rankine cycle (ORC) system. This system may use a variety of heat storage materials, including solids, liquids, and phase change materials (PCM). This article discusses the use of PCM as a thermal energy storage material in TES systems coupled with ORC systems. Other TES configurations may be used in ORC; however, in this article, the TES is solely used in heat exchangers, i.e., evaporator and liquid heater. The goal of this research is to establish a dimensionless storage mass parameter for sizing TES-evaporator (TES-EVA) or TES-liquid heater (TES-LH) devices for ORCs. Furthermore, the model of this system was created in the MATLAB environment using the chosen hydrocarbons as ORC working fluids. The obtained modelling results provide a novel point of view that scientists and engineers may employ while developing the TES-EVA or TES-LH utilizing PCM for ORC.

Keywords: sizing method; heat exchanger; thermodynamic analysis; TES-EVA; TES-LH



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1. Introduction

Thanks to the positive features of the organic Rankine cycle/ORC (such as, for example, the possibility of application of different low-boiling working fluids and therefore flexibility to different alternative heat sources), this technology is considered promising and can be employed for a wider operating temperature range than in the case of standard steam power plants with an operating principle based on the implementation of Clausius–Rankine cycle. Research in the field of ORC systems is currently focused on the working fluids selection, innovative designs of the expanders, optimized system configuration, and fitting the systems to the heat sources. A literature review proves [1–6] that there is a significant increase in interest in the use of ORC systems for energy harvesting from intermittent heat sources, such as solar thermal energy, ocean thermal energy, industrial and residential waste heat, etc. In order to have sustainable power generation, energy harvesting from some intermittent heat sources has to proceed differently than it is usually done in the case of other alternative heat sources [7]. Intermittent heat sources often feature floating thermal and output characteristics which negatively influence the operating conditions and continuity of ORC system operation. To address the issue of using intermittent heat for powering ORC systems and power generation, the application of thermal energy storage (TES) device or system appears promising. By the application of the TES device or system, the thermal energy can be stored; therefore, the ORC system operation and sustainability can be improved [7,8].

Nowadays, research related to thermal energy storage is very intensive. The possible materials (both sensible and latent) for thermal energy storage devices and systems are investigated. Researchers are also focusing on optimization of the dynamics of TES devices charging and discharging and selection of TES devices and systems to the given heat source and energy receiver. However, comprehensive research on the coupled TES and ORC systems is still missing.

A literature review shows that a few papers are treating coupled TES and ORC systems, and most of these papers are related to systems applied for solar thermal energy conversion. Costa S-C et al. [9] analyzed the use of latent thermal energy storage for a small solar power plant equipped with the ORC system. The authors numerically analyzed the use of ribs without thermal bonding as a method to improve heat transfer in phase-change thermal energy storage material (PCM). It was found that the lack of thermal connection between the fins and heat tubes does not significantly affect the time of TES charging and discharging, and that better results are achieved by using aluminum fins instead of fins made of steel. In an article [10], the authors thermodynamically analyzed two configurations of solar ORC systems (i.e., direct and indirect). In these systems, TES devices using PCM were applied to stabilize energy generation. In this study, the authors used 1,1,1,3,3-Pentafluoropropane (R245fa) as the ORC working fluid (both in the direct and indirect system), while water was used as the heat transfer fluid in the indirect system. It was estimated that the direct system featured higher thermal efficiency. Li S. et al. [11] analyzed the dynamic performance of a small solar ORC system coupled with thermal energy storage. In a study [8], the authors analyzed a small solar system for domestic applications based on ORC integrated with TES. Different energy storage strategies were analyzed in this paper. It was estimated that in the strategy of full energy storage and system adjustment to the evening peak of demand, about 20% more electrical power can be obtained using PCM thermal energy storage material compared to water.

There are several possible configurations of TES and ORC systems [12]. Literature detailing the properties of TES is governed by the studies related to heat storage materials, the method of storing thermal energy, and the TES applications [13]. The selection of suitable heat storage material for TES dedicated for application in the ORC system appears to be one of numerous elements encouraging research and playing an important role in the transition to sustainable energy [13–15]. The heat storage material used in the TES applied in the ORC system has a major impact on the size of the TES device or system. In prior work [16], the sizing of a sensible-heat TES device in an ORC system utilizing specified heat storage materials revealed a trend in the device size using dimensionless storage mass parameters $\zeta(T)$. Using this dimensionless storage mass parameter provides a fresh perspective in designing the TES for ORC. The issue of the thermal energy storage selection for the ORC system was also raised in our previous work [16]. In that paper, we reviewed and analyzed materials that can be used in TES devices coupled with ORC. An evaluation parameter was also proposed for the selection of heat storage material for the given ORC working fluid. Analyses were carried out for different sensible materials (PCMs were not considered) using their specific heat capacity.

The review of the previous works carried out in the field of cooperation of TES devices and systems with ORCs shows that this research area is not yet fully recognized and worth investigating. The authors most often conducted analyses and studies about selected thermal energy storage materials with selected working fluids in specific applications, most often in solar micro-installations. However, there is a lack of comprehensive analysis of the selection of heat storage materials (i.e., solids, liquids and PCMs) for different ORC working fluids and operating conditions. An attempt to fill this gap has been made in this paper.

This work reports the results of modelling of TES scaling, which can be applied in low- and medium-temperature ORC systems. It was considered that TES will use PCMs. This work aims to investigate the trend of $\zeta(T)$ parameter based on the combination of PCM and selected hydrocarbons (HCs) as ORC working fluids. The HCs are chosen in this analysis

as these working fluids have a low global warming potential (GWP). The model of the ORC system coupled with TES was implemented in a MATLAB environment, and the TES arrangement is considered within the heat exchangers (liquid heater and evaporator).

This paper is structured as follows. The next section introduces the novel thermal energy storage for the ORC system, the features that influence the performance of the TES device, and the proposed modelling system to demonstrate the computation procedure. Section 3 reported the overall simulated results. Furthermore, Section 4 discusses findings on thermal storage characteristics and size. In the end, the paper is summarized by the conclusions of the study.

2. A Novel Thermal Energy Storage for Organic Rankine Cycle

2.1. The Proposed ORC Employing TES

Organic Rankine cycle (ORC) is essentially a Rankine cycle in which organic working fluid is used instead of water. The design and technical structure of the ORC system are mostly determined by the thermodynamic and chemical properties of a low-boiling working fluid used in the cycle. The scheme of the ORC power plant coupled with TES-EVA and TES-LH and thermodynamic processes of the cycle for a typical working fluid are illustrated in Figure 1.

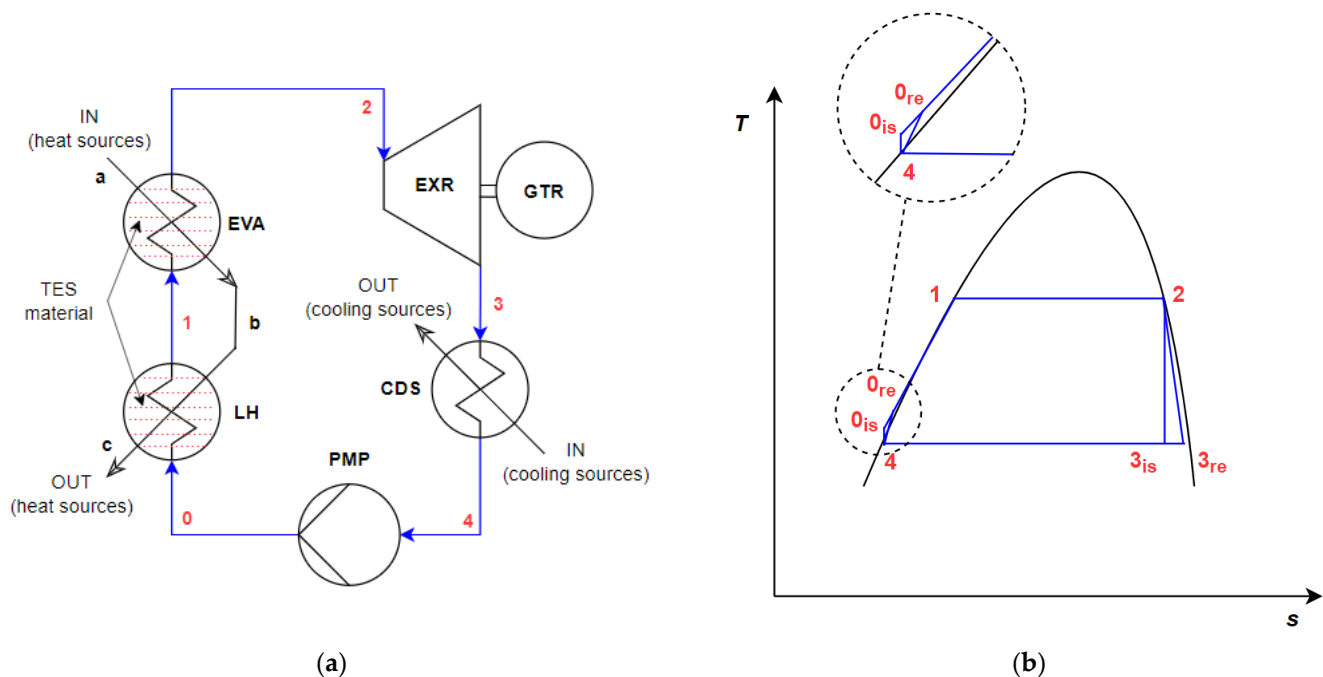


Figure 1. The scheme of the ORC system integrated with thermal energy storage evaporator (TES-EVA) and thermal energy storage liquid heater (TES-LH) (a) schematic layout of ORC with TES materials, and (b) the process in T-s diagram.

The heat carrier enters the pipeline and then passes via an assembly of heat exchangers, (pre-heater, evaporator, and eventually superheater) where heat is transferred to the low-boiling organic working fluid circulating in the ORC system. The low-boiling working fluid is therefore heated and evaporated in the evaporator (EVA). It is usually assumed that heat addition in this process is isobaric (0–2). In most cases, this process is preceded by liquid working fluid preheating which is proceeded in a pre-heater (or liquid-heater/LH), during the isobaric process of heat addition (0–1). In some ORC systems, an extra heat exchanger might be installed to superheat the working fluid. When the high-pressure vapor reaches point 2, it is forced to the inlet of the expander in which its thermodynamic properties are reduced, vapor is expanded, and thermal energy is converted into mechanical energy of the rotating shaft. In most cases, the working fluid thermodynamic parameters after

expansion in the expander are in the superheated range (i.e., many of the working fluids used in ORC applications are a so-called dry-type [17]). However, the process in Figure 1 is illustrated for typical wet working fluid; therefore, the end of the expansion process may remain in the wet vapor condition (i.e., the degree of vapor quality is between 0 and 1, $0 < x < 1$). In an ideal case, the process of 2–3_{is} is called the isentropic expansion (where point 3_{is} denotes the process at point 3 in an isentropic condition); however, due to the irreversibility of the expansion, the course of this process in a real case is as denoted by 2–3_{re}. If it is economically feasible, an extra heat exchanger (regenerator) can be added after the expander to recover some of the sensible heat of the superheated vapor and transfer this recovered heat to the working fluid entering the liquid heater. However, in the simple configuration of the ORC system, which is illustrated in Figure 1, the regenerator is not applied. After expansion in the expander, the working fluid enters the condenser and is rejecting heat to the cooling fluid until values of its thermodynamic properties reach the thermodynamic state described by point 4. This process refers to an isobaric process of cooling and condensation during which working fluid changes its phase from vapor to liquid. After that, the cycle closes while condensed working fluid is pumped again by the pump and its thermodynamic properties reach the thermodynamic state described by point 0. In an ideal example, pumping is isentropic, and the course of this process is as denoted by 4–0_{is} (where 0_{is} denotes the isentropic process at point 0). In real operating conditions, the pumping process is not isentropic and its course is different (which is denoted by 0_{re}). Each mathematical model of the above-described processes is given in Section 2.2, as well as the description of the heat transfer that is proceeding in the TES materials.

The type of low-boiling working fluid indicated above has a considerable impact on the performance (i.e., operating conditions, thermodynamic parameters, efficiency, etc.) of ORC systems. Therefore, Section 2.3 discusses the selection of the working fluid. The description includes the working fluid properties and parameters that must be taken into account in the current scenario of environmental regulations in order to reduce the negative environmental effects that may be caused by selected types of low-boiling working fluids.

In the proposed system, TES material may be applicable for the ORC system to enable the possibility of thermal energy storage within the system. Different configurations of TES devices and ORC systems can be considered [12]. However, in this study, we focus on the application of TES material in the evaporator and liquid heater as it is presented in Figure 1a. This application allows storing and efficiently using the intermittent heat (i.e., fluctuated heat) that comes from floating renewable sources (such as, for example, geothermal, solar thermal, ocean thermal heat, etc.) or other intermittent heat sources (such as, for example, industrial waste heat). As it is seen in the schematic layout (refer to Figure 1a), the evaporator and liquid heater are combined with the TES materials, which are indicated by red dots in the scheme. In this case, the combination of these systems is so-called TES-EVA and TES-LH.

Sensible heat, latent heat, and chemical processes are some mechanisms that might be used in TES [13,15,18]. In this study, the latent heat (i.e., phase change material/PCM) is used to analyze TES-EVA and TES-LH size. Due to the use of PCMs in these heat exchangers, the maximum operating temperature of the liquid heater and the evaporator is assumed as the melting temperature of the PCMs. The selection of PCMs is described in Section 2.4.

2.2. General Mathematical Model Description

Heat carriers with certain thermodynamic properties and mass flow rate enter the evaporator through pipeline, gives up the heat to the low-boiling working fluid, and then its flow is forced to the liquid heater. The energy balance of these heat exchangers (see Figure 1) can be described by Equations (1) and (2) for the evaporator and Equations (3) and (4) for the liquid heater, respectively:

$$\dot{Q}_{a \rightarrow b} = \dot{Q}_{1 \rightarrow 2} = \dot{Q}_{\text{EVA}}, \quad (1)$$

$$\dot{m}_{hs}c_{hs}(\Delta T_{a \rightarrow b}) = \dot{m}_{wf}\Delta h_{1 \rightarrow 2}, \quad (2)$$

$$\dot{Q}_{b \rightarrow c} = \dot{Q}_{0 \rightarrow 1} = \dot{Q}_{LH}, \quad (3)$$

$$\dot{m}_{hs}c_{hs}(\Delta T_{b \rightarrow c}) = \dot{m}_{wf}\Delta h_{0 \rightarrow 1}. \quad (4)$$

where $\dot{Q}$, $\dot{m}$, c , ΔT , and Δh describe the heat transfer rate, mass flow rate, specific heat capacity, temperature change, and specific enthalpy change of the working fluids, respectively. What is more, hs and wf are subscripts for the heat source and working fluid, respectively. Furthermore, other subscripts indicated in Equations (1)–(4) relate to the process in Figure 1. In the considered case, the heat carrier and low-boiling working fluid flow is countercurrent. The energy balance of heat source and working fluid may be calculated as a function of enthalpy or temperature changes.

Figure 1 shows that the thermal energy storage (TES) is applied in the heat exchangers (evaporator and liquid heater) indicated with red dots. The amount of thermal energy which is stored in the device can be calculated using Equation (5):

$$Q_{TES} = V_{TES}\rho_{TES}c_{TES}\Delta T_{2 \rightarrow env}, \quad (5)$$

where Q , V , ρ , c , and ΔT are the stored amount of thermal energy, volume, density, specific heat capacity, and temperature change of TES material, respectively. Moreover, env is the subscript for environmental conditions. The specific heat capacity of TES material can be determined, for example, by using differential scanning calorimetry [19], and this parameter is temperature-dependent. The general polynomial equation for the specific heat capacity of different thermal energy materials is described in Equation (6) [16,20]:

$$c_{TES} = c_0 + c_1T^1 + c_2T^2 + c_3T^3 + \dots + c_nT^n, \quad (6)$$

where $c_0 \dots c_n$ are experimentally obtained polynomial constants, which values are different for different thermal energy storage materials and collected in substance properties sources [20].

In the case of phase change material (solid-liquid), the specific heat capacity can be described by Equations (7) and (8) [21]:

$$\vartheta = 1 - \lambda \quad (7)$$

$$c_{l,s} = \vartheta c_l + (1 - \vartheta)c_s \quad (8)$$

where ϑ and λ represent liquid and solid fractions, respectively. Moreover, the subscripts of l and s represent a phase of liquid and solid, respectively.

In this paper, we defined a dimensionless parameter that can be treated as an assessment criterion that can be applied for sizing the TES devices and systems combined with ORCs by assessing the mass of thermal energy storage material which is needed to be applied in TES device. This dimensionless storage mass parameter ($\zeta(T)$) can be defined and calculated using Equation (9) [16]:

$$\zeta(T) = \frac{m_{TES}}{m_{wf}} = \frac{\Delta h_{HE}}{c_{TES}(T_{TES})|_{T_{TES1}}^{T_{TES2}}(T_{TES1} - T_{TES2})}. \quad (9)$$

where m is mass and the subscript of HE refers to the heat exchanger used in the ORC system. By using Equation (9), it is possible to estimate the mass of TES material required to store thermal energy which is needed to change the enthalpy of the low-boiling organic working fluid inside the ORC system by a certain level. If the melting enthalpy data is available, the $\zeta(T)$ parameter can be also computed using this melting enthalpy by Equation (10):

$$\zeta(T) = \frac{m_{TES}}{m_{wf}} = \frac{\Delta h_{HE}}{\Delta h_{melting}}. \quad (10)$$

The $\zeta(T)$ parameter for liquid heater and evaporator (see, Figure 1a) can be calculated by Equations (11) and (12), respectively:

$$\zeta(T) = \frac{\Delta h_{0re \rightarrow 1}}{c_{TES}(T_{TES})|_{T_{TES2}}^{T_{TES1}}(T_{TES1} - T_{TES2})} = \frac{\Delta h_{0re \rightarrow 1}}{\Delta h_{melting}}, \quad (11)$$

$$\zeta(T) = \frac{\Delta h_{1 \rightarrow 2}}{c_{TES}(T_{TES})|_{T_{TES2}}^{T_{TES1}}(T_{TES1} - T_{TES2})} = \frac{\Delta h_{1 \rightarrow 2}}{\Delta h_{melting}}. \quad (12)$$

After heat is transferred to the organic low-boiling working fluid in the liquid heater and evaporator using TES, the energy flow in the following processes may be described by Equations (13)–(15) for the expander, condenser, and pump, respectively:

$$P_{EXR} = \dot{m}_{wf}(h_1 - h_{2is})/\eta_{is,EXR}, \quad (13)$$

$$\dot{Q}_{CDS} = \dot{m}_{wf}(h_{2re} - h_3), \quad (14)$$

$$P_{PMP} = \dot{m}_{wf}(h_{4is} - h_3)/\eta_{is,PMP}. \quad (15)$$

where P is the power (of a pump or an expander) and $\eta_{is,EXR}$ and $\eta_{is,PMP}$ is the internal efficiency (isentropic efficiency) of expander and pump, respectively. In this study, the internal efficiency of the expander and pump is set as 0.8 and 0.7, respectively, which are the mean values of the internal efficiency of turbo- and volumetric expanders and pumps that are applied in ORCs [22–27]. The isentropic and real processes for expander and pump are indicated by the subscripts of *is* and *re*, respectively. For an ORC system, not only system power can be calculated and used as an assessment criterion for rating different ORCs, but also the overall cycle efficiency can be determined as an even more important comparative indicator. Equation (16) can be used to obtain the overall ORC system efficiency:

$$\eta_{ORC} = \frac{P_{EXR} - P_{PMP}}{\dot{Q}_{LH} + \dot{Q}_{EVA}}. \quad (16)$$

2.3. The Selection of Working Fluids

The selection of low-boiling working fluid to the ORC system is one of the key design challenges. The type of the selected working fluid and its thermodynamic, chemical, and physical properties are highly influencing the ORC system design (i.e., size and type of heat exchangers, type of the expander and pump that can be applied for selected working fluid) and its performance (i.e., power output, efficiency, etc.). The selection criteria of the working fluid consider the thermodynamic cycle design, its operating conditions and efficiency, environmental impact of the working fluid, working fluid safety (i.e., toxicity, flammability, explosivity, radioactivity, etc.), corrosivity, chemical stability, and economic viability [3,28–30]. Since the typical working fluids used in ORCs are also utilized in refrigeration and air conditioning systems, the safety criterion for working fluids relates to the American Society of Heating, Refrigerating, and Air-conditioning Engineers (ASHRAE) standards [31].

The selection of working fluids based on the ozone depletion potential (ODP) and global warming potential (GWP) parameters is an example of an environmentally friendly approach to designing the ORC system. The ODP is a measure of the relative amount of ozone layer degradation, whereas GWP is a measure of how much a certain quantity of gas contributes to global warming over a specific time period. The GWP of carbon dioxide (CO₂) is a common reference parameter. According to environmental concerns, the material, such as chlorofluorocarbons (CFCs), halons, and hydrochlorofluorocarbons (HCFCs) are not suitable for use as working fluids in any further system, as most of them are either banned by Montreal, Kyoto protocols, Kigali Amendment, or are being currently phased-out [32,33].

Due to this environmental issue, some low-GWP working fluids, such as CO₂, ammonia, and hydrocarbons (HCs) are applied in selected systems [34]. Several studies have documented the use of HCs as a working fluid in a variety of applications. Some HCs have been tested as working fluids in ORC systems to recover cold energy emitted during liquefied natural gas (LNG) regasification. Using Propane as a working fluid, it is possible to recover up to 332.06 MW of cold energy in the forthcoming LNG regasification system (2020–2023) using seawater as a heat source [35]. According to one research, the application of HCs and their mixture resulted in outstanding cycle performance [36]. A study on the performance of geothermal ORC with chosen HCs has also been carried out [37]. Furthermore, an advanced exergoeconomic study on ORC employing HCs revealed that certain HCs perform promising performances in terms of the levelized energy cost [38]. Since it appears that the application of HCs as a working fluid is prospective in the future, several HCs are chosen for the investigation in this study. The list of these working fluids is collected in Table 1 with their basic thermodynamics' properties, where T_{boiling} , T_{crit} , P_{crit} , and T_{triple} refer to the boiling temperature at atmospheric pressure, the temperature at a critical point, pressure at a critical point, and temperature at the triple point, respectively.

Working fluids that are applied in ORCs are traditionally categorized into three types: wet, isentropic, and dry [30,39,40]. A new classification based on A-C-M-N-Z points is nowadays used to identify the working fluids based on the critical, triple point temperatures, and the local maximal–minimal entropies on the saturation curve of working fluids [41]. The chosen hydrocarbons may also be categorized into these points, as shown in Table 1. This sort of investigation is important for estimating the expansion route in the ORC system (i.e., the wet or dry expansion process) as well as the description of heat transfer in fluid dynamics [42,43].

Table 1. The list of selected hydrocarbon working fluids and their basic thermodynamic properties.

Name of Working Fluid	CAS no. [44]	Type of Working Fluid [41]	T_{boiling} (K)	T_{crit} (K) [44]	P_{crit} (MPa) [44]	T_{triple} (K) [44]
Propane	74-98-6	ACZ	231.03	369.89	4.25	85.52
Butane	106-97-8	ACNMZ	272.65	425.12	3.79	134.89
Butene	106-98-9	ACNMZ	266.84	419.29	4.00	87.80
Pentane	109-66-0	ANCMZ	309.20	469.70	3.36	143.47
Isobutane	75-28-5	ACNMZ	261.40	407.81	3.62	113.73
Isobutene	115-11-7	ACNMZ	266.14	418.09	4.00	132.4
Isopentane	78-78-4	ANCMZ	300.97	460.35	3.37	112.65

Table 1 describes the various types of seven selected HC working fluids utilized in the investigation. ACZ, ACNMZ, and ANCMZ kinds tend to be picked as representatives. The use of ACZ-type working fluid in the ORC system indicates that the expansion process will take place under wet vapor conditions. Moreover, ACNMZ and ANCMZ have the potential to expand the working fluid under both conditions (i.e., dry or wet vapor).

Table 1 includes certain thermodynamic properties of selected working fluids, such as triple point temperature, boiling temperature, critical temperature, and critical pressure. The information on triple point temperature and critical temperature is provided to demonstrate that the ORC is designed in such a way that system operating parameters will fit between these temperatures. The critical pressure is used to evaluate the maximum working fluid pressure at the inlet to the expander. Furthermore, the boiling temperature denotes that below this temperature, vacuum equipment, such as a vacuum pump is necessary to be applied in the condenser of the ORC system. The thermal properties of the working fluids in Table 1 were taken from CoolProp [44].

2.4. The Selection of PCM

Among different TES technologies and materials, heat storage using PCMs is found to be one of the most efficient methods of thermal energy storage [45–47]. PCM provides

higher thermal energy storage capacity and more isothermal behavior during TES discharging and charging compared to sensible heat storage materials [48]. At a certain temperature, PCMs may store and release substantial quantities of thermal energy during melting and solidification. Different PCMs can be classified as solid-solid, solid-liquid, liquid-gas, or solid-gas, as illustrated in Figure 2.

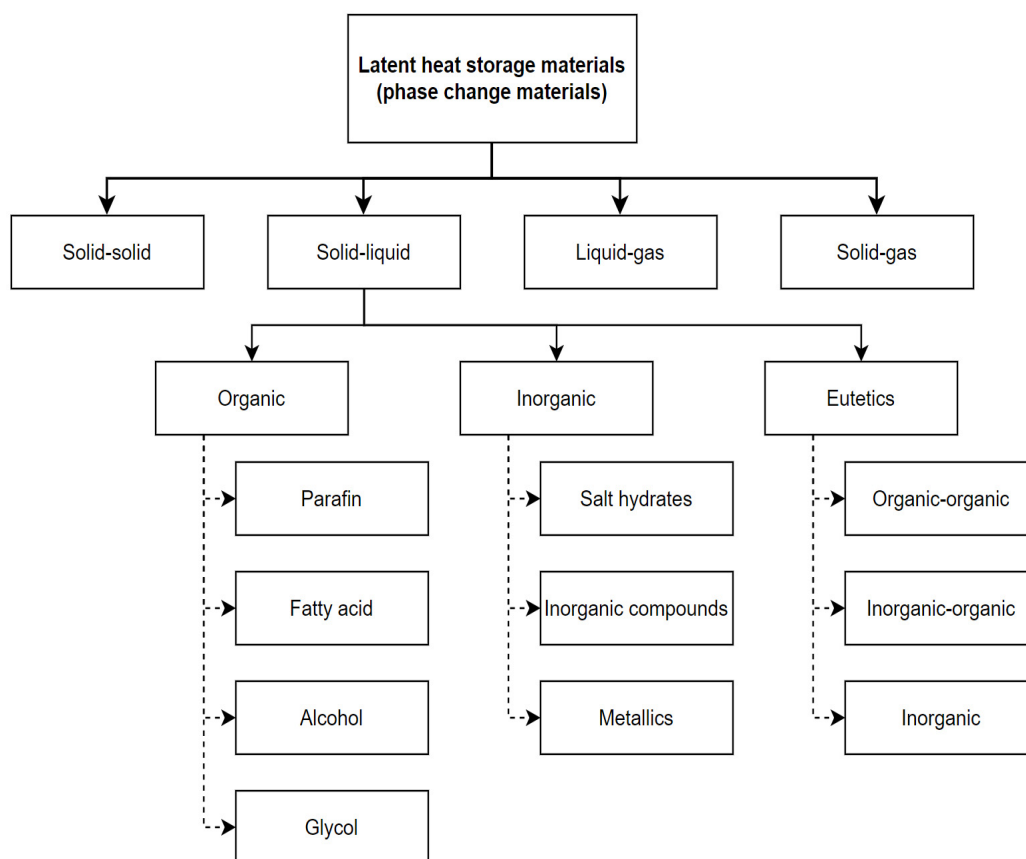


Figure 2. The classification of solid-solid, solid-liquid, liquid-gas, and solid-gas latent heat storage materials (PCMs), adapted from [49,50].

Solid-liquid PCMs can be used to store a large quantity of thermal energy and this type of material includes different chemical substances, such as organic, inorganic, and eutectics, which are illustrated in Figure 2. It seems that solid-liquid PCMs are promising to be applied in many applications, such as space heating and cooling of buildings [51–53], solar energy applications [54–58], etc. The solid-liquid PCMs also offer a wide operating temperature range (which is the physical property of a material and varies for different types of PCMs). Given that, there is a set of important material properties (e.g., safety and environmental issues, economic viability, thermophysical properties, nucleation and crystal growth ability, chemical properties, etc.) that should be taken into account during the TES device design phase and selection of TES material. In this investigation, the authors focused the analysis on these PCMs for which melting temperature is in the range of 90–200 °C (363.15–473.15 K), which is the temperature range characteristic for low-temperature alternative heat sources (e.g., solar thermal energy, geothermal, and waste heat). These heat sources are often used for powering low-temperature ORC systems [59]. For this range of operating temperatures, different types of solid-liquid-type PCMs were selected for further analysis. The list of these materials is summarized in Table 2 with values of their melting temperature and melting enthalpy. The lowest value of melting temperature in the given range of temperature was found for $\text{Mg}(\text{NO}_3)_2 \cdot 6\text{H}_2\text{O}$ while the highest was found for Galactitol.

Table 2. The list of selected PCMs with their classification, melting temperature and enthalpy.

No	PCM Name	Types	Classifications	Melting Temperature (K)	Melting Enthalpy (kJ/kg)	Refs.
1	Mg(NO ₃) ₂ ·6H ₂ O	Inorganic	Salt hydrates	363.15	163	[60]
2	Xylitol	Organic	Sugar alcohols	367.15	263	[60]
3	Alpha naphthol	Organic	Non paraffin	369.15	163	[49,50,61]
4	D-sorbitol	Organic	Sugar alcohols	370.15	185	[60]
5	Glutaric acid	Organic	Non paraffin	370.65	156	[49,50,61]
6	p-Xylene dichloride	Organic	Non paraffin	373.15	138.7	[49,50,61]
7	Methyl fumarate	Organic	Fatty acids	375.15	242	[49,50,61]
8	Catechol	Organic	Non paraffin	377.45	207	[49,50,61]
9	Quinone	Organic	Non paraffin	388.15	171	[49,50,61]
10	Acetanilide	Organic	Non paraffin	388.15	142	[49,61]
11	MgCl ₂ ·6H ₂ O	Inorganic	Salt hydrates	390.15	169	[50,60,61]
12	Succinic anhydride	Organic	Non paraffin	392.15	204	[49,50]
13	Erythritol	Organic	Sugar alcohols	393.15	340	[60]
14	Benzoic acid	Organic	Non paraffin	394.85	142.8	[49,61]
15	Stibene	Organic	Non paraffin	397.15	167	[49,50,61]
16	Benzamide	Organic	Non paraffin	400.35	169.4	[49,50,61]
17	67% KNO ₃ + 33% LiNO ₃	Eutectics	Inorganic mixtures	406.15	170	[60,62]
18	Polyethylene	Organic	Paraffins	408.15	200	[60]
19	Phenacetin	Organic	Non paraffin	410.15	136.7	[49,61]
20	53% KNO ₃ + 40% NaNO ₂ + 7% NaNO ₃	Eutectics	Mixtures	415.15	80	[62]
21	Acetyl-p-toludene	Organic	Non paraffin	419.15	180	[49,61]
22	Phenylhydrazon benzaldehyde	Organic	Non paraffin	428.15	134.8	[49,61]
23	Salicylic acid	Organic	Non paraffin	432.15	199	[49,61]
24	Benzanilide	Organic	Non paraffin	434.15	162	[49,61]
25	O-Mannitol	Organic	Non paraffin	439.15	294	[49,61]
26	D-Mannitol	Organic	Sugar alcohols	440.15	316	[60]
27	Hydroquinone	Organic	Non paraffin	445.55	258	[49,61]
28	p-Aminobenzoic acid	Organic	Non paraffin	460.15	153	[49,61]
29	Galactitol	Organic	Sugar alcohols	461.15	351	[60]

3. Results

The total efficiency of the ORC system is a key assessment parameter that is used to compare different ORCs in terms of design, performance, and operating parameters. Recent papers [63,64] investigated the maximum efficiency of the ORC based on the characteristic of working fluids and specified operating temperature ranges. A similar method was used in this work to obtain the maximal ORC efficiency which can be obtained for specified working fluids and system operating conditions. Therefore, the temperature of the working fluid at the outlet of TES-EVA and inlet to the expander (i.e., T_2) for the maximal ORC efficiency may be computed. The temperature computed for maximum ORC efficiency, as indicated in Table 3, is the boundary condition for the chosen working fluid in this study (see, Table 1 in Section 2.3 for detailed information on critical parameters of selected working fluids). Temperatures over this level were not considered.

In Table 3, T_4 , T_2 , ΔT_2 , and $\eta_{\max, \text{ORC}}$ represent the temperature of working fluids at the inlet of the pump, expander, the calculation increment steps, and the maximal efficiency of ORC, which were applied in simulation, respectively. Table 3 indicates that each working fluid has a different T_2 temperature for maximum ORC efficiency at the same boundary conditions related to the thermodynamic cycle (i.e., the internal efficiency of the expander and pump, as well as the temperature level of the working fluid at the inlet of the pump). The obtained temperatures appear to be around 5 K below the critical temperature. This temperature level at maximum ORC efficiency was utilized as the maximum operating temperature, so the PCM may be chosen and fitted to the required

condition where the melting temperature is the operational temperature of the TES-EVA applied in the ORC system.

Table 3. The temperature at a maximum ORC efficiency simulated with $\eta_{is,EXR}$ and $\eta_{is,PMP}$ at 0.8 and 0.7, respectively.

Name of Working Fluid	T ₄ (K)	ΔT ₂ (K)	η _{max,ORC} (—)	T ₂ (η _{max,ORC}) (K)
Propane	303.15	0.01	0.0913	365.55
Butane	303.15	0.01	0.1487	420.15
Butene	303.15	0.01	0.1446	413.04
Pentane	303.15	0.1	0.1792	466.45
Isobutane	303.15	0.01	0.1320	403.20
Isobutene	303.15	0.01	0.1427	412.01
Isopentane	303.15	0.01	0.1714	457.54

Table 4 shows a matrix of possible cases which can be created based on the above-mentioned boundary constraint. The symbol in Table 4 also indicates the kind of working fluid. Because the maximum ORC working temperature for Propane is 365.55 K (see, Table 3), only Mg(NO₃)₂·6H₂O in Table 2 may be utilized as PCM. This is likewise the case for the PCM used for other working fluids; therefore, 132 possible cases were considered during modelling simulations proceeded in MATLAB using the mathematical model of the system described in detail in Section 2.2.

Table 4. A matrix of possible simulation cases for selected working fluids and PCMs based on the boundary conditions.

No Refers to Table 2	Propane	Butane	Butene	Pentane	Isobutane	Isobutene	Isopentane
1	o	+	*	Δ	◇	▽	□
2	-	+	*	Δ	◇	▽	□
3	-	+	*	Δ	◇	▽	□
4	-	+	*	Δ	◇	▽	□
5	-	+	*	Δ	◇	▽	□
6	-	+	*	Δ	◇	▽	□
7	-	+	*	Δ	◇	▽	□
8	-	+	*	Δ	◇	▽	□
9	-	+	*	Δ	◇	▽	□
10	-	+	*	Δ	◇	▽	□
11	-	+	*	Δ	◇	▽	□
12	-	+	*	Δ	◇	▽	□
13	-	+	*	Δ	◇	▽	□
14	-	+	*	Δ	◇	▽	□
15	-	+	*	Δ	◇	▽	□
16	-	+	*	Δ	◇	▽	□
17	-	+	*	Δ	-	▽	□
18	-	+	*	Δ	-	▽	□
19	-	+	*	Δ	-	▽	□
20	-	+	-	Δ	-	-	□
21	-	+	-	Δ	-	-	□
22	-	-	-	Δ	-	-	□
23	-	-	-	Δ	-	-	□
24	-	-	-	Δ	-	-	□
25	-	-	-	Δ	-	-	□
26	-	-	-	Δ	-	-	□
27	-	-	-	Δ	-	-	□
28	-	-	-	Δ	-	-	-
29	-	-	-	Δ	-	-	-

The 132 cases collected in Table 4 may be represented in Figure 3 by the computed values of the $\zeta(T)$ parameter and TES-EVA temperature, i.e., $(\zeta(T_2)-T_2)$ diagram. The outcome displays the size parameter for each working fluid and PCM pair. There are two types of data illustrated in Figure 3, the $\zeta(T)$ parameter for evaporator (red colours) and liquid heater (blue colours). Since there are several PCMs in the TES-EVA and TES-LH operating temperature ranges of 362–378 K and 388–412 K, it appears that the data is dense in Figure 3. Therefore, the magnification of this data is illustrated in Figures 4 and 5.

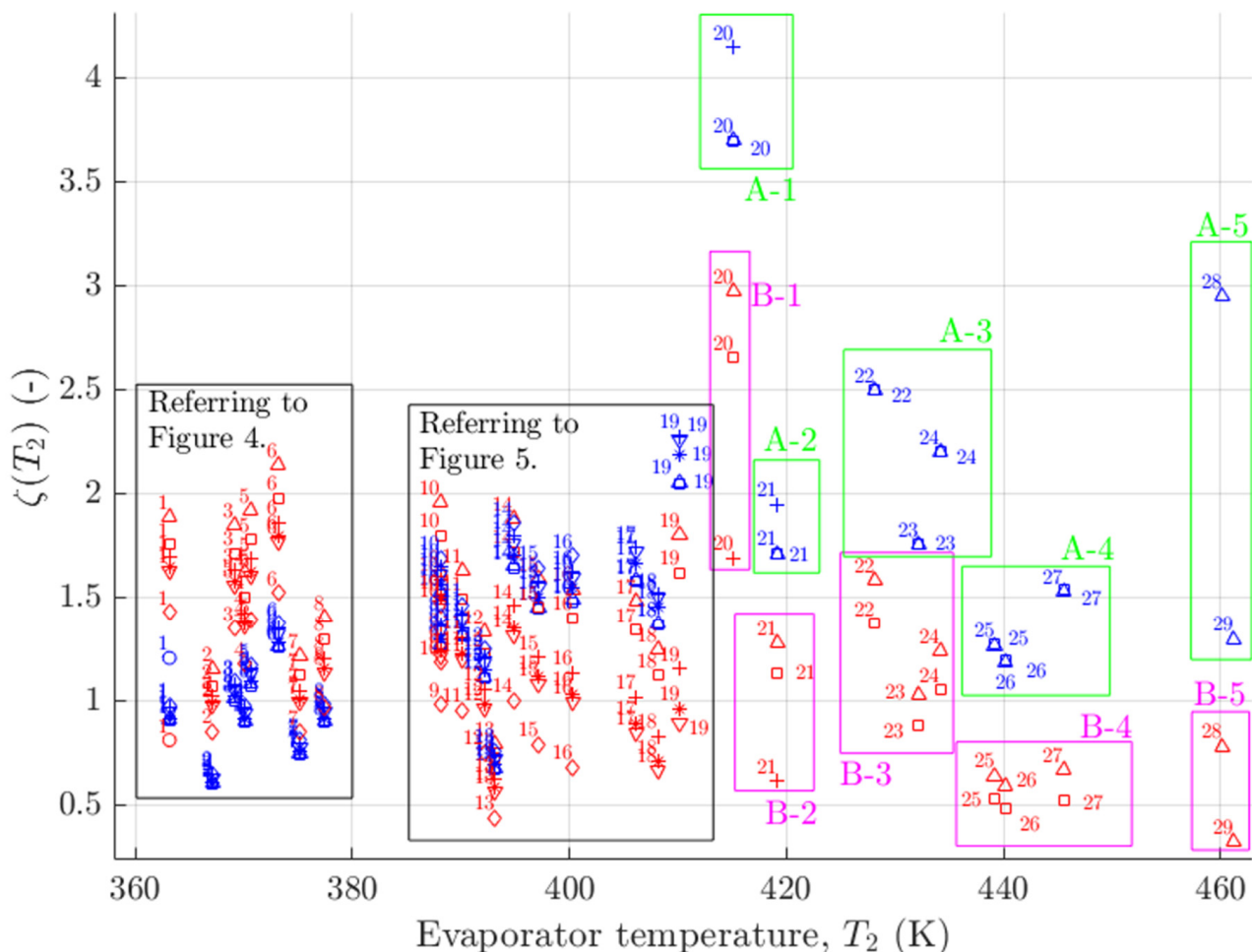


Figure 3. The obtained modelling results in $\zeta(T_2)-T_2$ diagram (the numbers 1–29 relate to the number of PCM listed in Table 2) for Propane, Butane, Pentane, Pentane, Isobutane, Isobutene, and Isopentane, which are represented by the circle, plus sign, asterisk, upward-pointing triangle, diamond, downward-pointing triangle, and square, respectively (blue and red colours refers to the calculation for liquid heater, i.e., TES-LH and evaporator i.e., TES-EVA, respectively).

Figure 3 shows that Butane and 53% $\text{KNO}_3 + 40\% \text{NaNO}_2 + 7\% \text{NaNO}_3$ pair (i.e., case marked as 20+) has the highest value of the $\zeta(T)$ parameter for the liquid heater ($\zeta(T_2) = 4.14$ at 415.15 K), while Pentane and Galactitol pair (i.e., case marked as 29 Δ) has the lowest value of the $\zeta(T)$ parameter for evaporator ($\zeta(T_2) = 0.32$ at 461.15 K). The lowest value of the $\zeta(T)$ parameter for the liquid heater is the pair of Isopentane and Xylitol (i.e., case marked as 2 $\square$) which indicates $\zeta(T_2) = 0.60$ at 367.15 K. The highest value of the $\zeta(T)$ parameter for evaporator is the pair of Pentane and 53% $\text{KNO}_3 + 40\% \text{NaNO}_2 + 7\% \text{NaNO}_3$ (i.e., case marked as 20 Δ), which indicates 2.97 at 415.15 K.

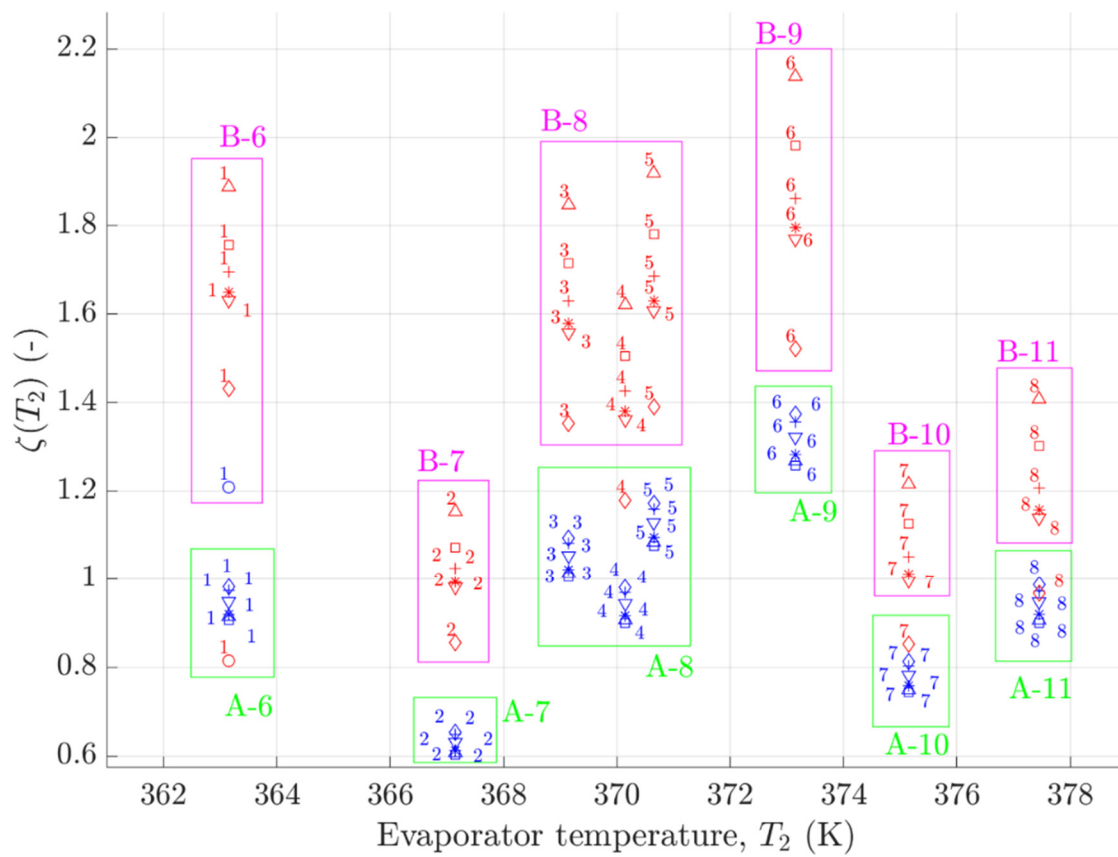


Figure 4. The obtained modelling results in $\zeta(T_2)$ – T_2 diagram for the evaporator temperature ranging between 362 K and 378 K (the numbers 1–29 relate to the number of PCM in Table 2) for Propane, Butane, Pentane, Pentane, Isobutane, Isobutene, and Isopentane which are represented by the circle, plus sign, asterisk, upward-pointing triangle, diamond, downward-pointing triangle, and square, respectively (blue and red colors refer to the calculation for liquid heater, i.e., TES-LH and evaporator i.e., TES-EVA, respectively).

Figure 3 shows data computed for chosen working fluids (Butane, Pentane, and Isopentane) and PCMs pairs at TES-EVA and TES-LH operating temperatures ranging from 413 K to 470 K. This figure also depicts the working fluid and PCM pair. The TES-LH and PCM groups are represented by green squares A-1, A-2, A-3, A-4, and A-5, whereas the TES-EVA and PCM groups are represented by magenta squares B-1, B-2, B-3, B-4, and B-5. In the temperature ranges of 413–470 K, it seems that the pair of selected working fluid and PCM for the liquid heater provides a greater value of $\zeta(T)$ parameter than in the case of the evaporator. This condition states that the enthalpy changes of a liquid heater at a given temperature and boundary condition are larger than that of an evaporator.

Figure 4 appears to represent a different view, with a greater value of the $\zeta(T)$ parameter of the evaporator at operating temperatures ranging from 362 K to 378 K. This situation is shown by the magenta box groups B-6, B-7, B-8, B-9, B-10, and B-11 being higher than the green box groups A-6, A-7, A-8, A-9, A-10, and A-11. However, it has been discovered that the pair of Propane and $\text{Mg}(\text{NO}_3)_2 \cdot 6\text{H}_2\text{O}$ produces distinct results, and the $\zeta(T)$ parameter behaves differently than Butane, Butene, Pentane, Isobutane, Isobutene, and Isopentane. $\zeta(T)$ parameter of Propane and $\text{Mg}(\text{NO}_3)_2 \cdot 6\text{H}_2\text{O}$ for liquid heaters is often greater than that of evaporators. In this situation, it corresponds to groups A-6 and B-6 in Figure 4.

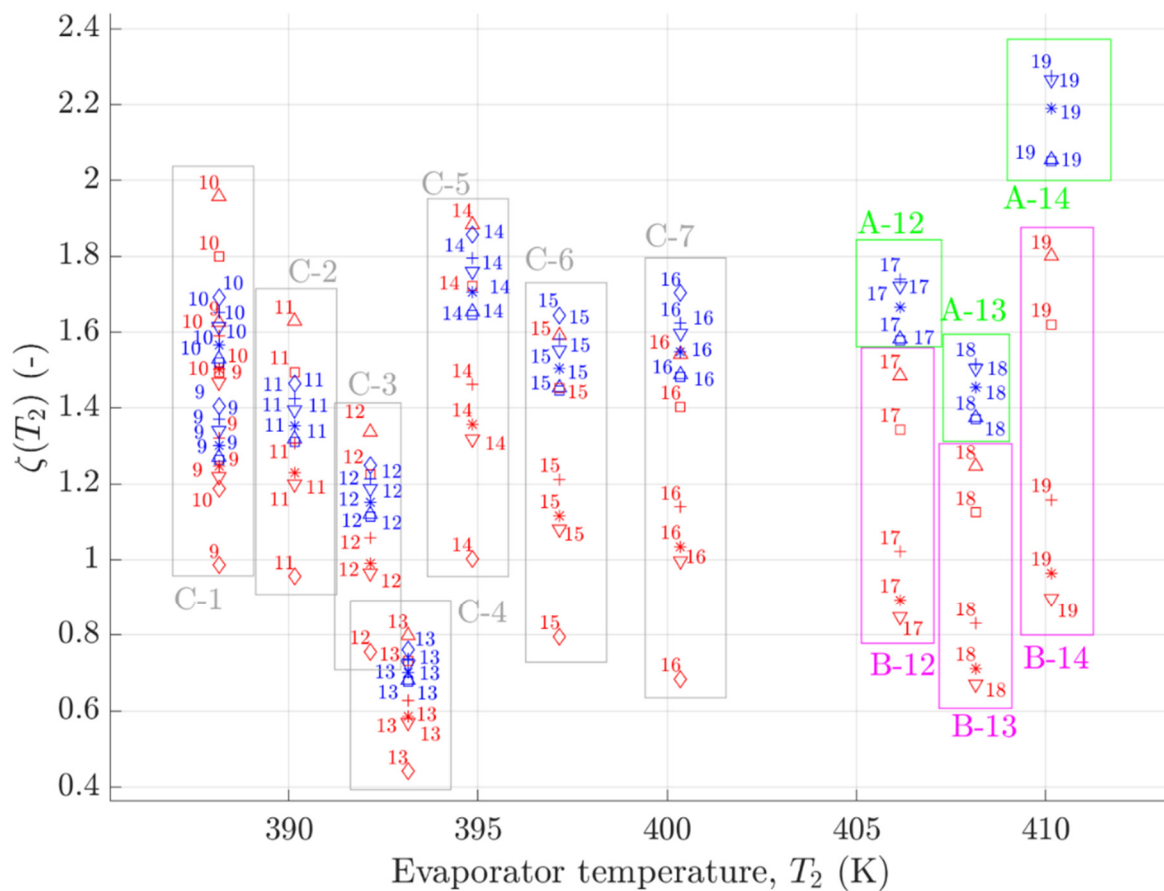


Figure 5. The obtained modelling results in $\zeta(T_2)$ – T_2 diagram for the evaporator temperature ranging between 388 K and 412 K (the numbers 1–29 relate to the number of PCM in Table 2) for Butane, Pentane, Pentane, Isobutane, Isobutene, and Isopentane which are represented by the plus sign, asterisk, upward-pointing triangle, diamond, downward-pointing triangle, and square, respectively (blue and red colours refer to the calculation for liquid heater, i.e., TES-LH and evaporator i.e., TES-EVA, respectively).

Figure 4 shows that isobutane pairs with PCM for evaporator offer the lowest values of $\zeta(T)$ parameter for evaporator (shown by the symbol of red diamond in the temperature ranges 366–378 K). This study demonstrates that, as compared to the other working fluids (i.e., Butane, Butene, Pentane, Isobutene, and Isopentane), Isobutane may be built with less PCM solely for evaporators. It is found that in the temperature ranges of 362–378 K, Pentane (i.e., case marked with symbol Δ in Figure 4) gives the largest value of the $\zeta(T)$ parameters for evaporator, which is illustrated in the magenta box groups B-6, B-7, B-8, B-9, B-10, and B-11. At the same temperature range, Isopentane (i.e., case marked with a symbol $\square$ in Figure 4) gives the lowest values of the $\zeta(T)$ parameters for the liquid heater, which is illustrated in the green box groups A-7, A-8, A-9, A-10, and A-11 (except for A-6, the lowest value of the $\zeta(T)$ parameter is obtained for Propane pairing with $\text{Mg}(\text{NO}_3)_2 \cdot 6\text{H}_2\text{O}$).

Figure 5 shows the $\zeta(T)$ parameter at operating temperatures ranging from 388 to 412 K. It appears that the obtained results differ from those shown in Figures 3 and 4. Figure 5 depicts the mixing of $\zeta(T)$ parameters (i.e., results are not forming groups like Figures 3 and 4). For this reason, the grey box group was established here to represent this circumstance. The grey box groups C-1, C-2, C-3, C-4, C-5, C-6, and C-7 are found between 388 and 402 K. It appears that the evaporator has about the same enthalpy change as the liquid heater. The grey box group is known as the transition area. Due to the influence of the shape of the saturation curve of the working fluid, raising the operating evaporator temperature will result in a reducing enthalpy change of the evaporator and a rising

enthalpy change of the liquid heater. It appears that Isobutane (marked with a symbol $\diamond$ in Figure 5) offers the lowest $\zeta(T)$ parameter pairing with Quinone, Acetanilide, $\text{MgCl}_2 \cdot 6\text{H}_2\text{O}$, Succinic anhydride, Erythritol, Benzoic acid, Stibene, and Benzamide, compared to the other working fluids.

Above 402 K, the results may be divided into two groups (marked with magenta and green boxes), indicating that the enthalpy change of the liquid heater is greater than that of the evaporator. As a result, at 402 K, the $\zeta(T)$ parameter for evaporator (shown in the magenta box in Figures 3 and 5) provides a lower value of $\zeta(T)$ parameter than liquid heater (shown in the green box in Figures 3 and 5). Moreover, it seems that Isobutene (indicated with a symbol ∇ in Figure 5) offers the lowest value of the $\zeta(T)$ parameter for evaporator pairing with 67% KNO_3 + 33% LiNO_3 , Polyethylene, and Phenacetin (illustrated in the magenta boxes B-12, B-13, and B-14).

4. Discussion

Based on the obtained results, it is suggested to use PCM for which the value of a $\zeta(T)$ parameter is less than 1 ($\zeta(T_2) < 1$) so that the TES-EVA or TES-LH uses less material to store the same amount of thermal energy. Therefore, such designed TES-EVA and TES-LH will feature smaller dimensions and lower investment costs. This finding may be valuable for engineers when designing an evaporator or liquid heater in conjunction with a PCM. The obtained results of working fluid pairing with PCM for modelling cases for which a $\zeta(T_2)$ parameter is less than 1 are collected in Table 5.

Table 5. A list of possible TES-EVA or TES-LH devices with a dimensionless storage mass parameter less than 1 ($\zeta(T_2) < 1$).

No	Working Fluid	PCM	T_2 (K)	T_4 (K)	$\zeta(T_2)$ (-)	Process
1	Propane	$\text{Mg}(\text{NO}_3)_2 \cdot 6\text{H}_2\text{O}$	363.15	303.15	0.81	TES-EVA
2	Isopentane	$\text{Mg}(\text{NO}_3)_2 \cdot 6\text{H}_2\text{O}$	363.15	303.15	0.90	TES-LH
3	Pentane	$\text{Mg}(\text{NO}_3)_2 \cdot 6\text{H}_2\text{O}$	363.15	303.15	0.91	TES-LH
4	Butene	$\text{Mg}(\text{NO}_3)_2 \cdot 6\text{H}_2\text{O}$	363.15	303.15	0.92	TES-LH
5	Isobutene	$\text{Mg}(\text{NO}_3)_2 \cdot 6\text{H}_2\text{O}$	363.15	303.15	0.94	TES-LH
6	Butane	$\text{Mg}(\text{NO}_3)_2 \cdot 6\text{H}_2\text{O}$	363.15	303.15	0.97	TES-LH
7	Isobutane	$\text{Mg}(\text{NO}_3)_2 \cdot 6\text{H}_2\text{O}$	363.15	303.15	0.98	TES-LH
8	Isopentane	Xylitol	367.15	303.15	0.60	TES-LH
9	Pentane	Xylitol	367.15	303.15	0.60	TES-LH
10	Butene	Xylitol	367.15	303.15	0.61	TES-LH
11	Isobutene	Xylitol	367.15	303.15	0.63	TES-LH
12	Butane	Xylitol	367.15	303.15	0.64	TES-LH
13	Isobutane	Xylitol	367.15	303.15	0.65	TES-LH
14	Isobutane	Xylitol	367.15	303.15	0.85	TES-EVA
15	Isobutene	Xylitol	367.15	303.15	0.98	TES-EVA
16	Butene	Xylitol	367.15	303.15	0.99	TES-EVA
17	Isopentane	D-sorbitol	370.15	303.15	0.89	TES-LH
18	Pentane	D-sorbitol	370.15	303.15	0.90	TES-LH
19	Butene	D-sorbitol	370.15	303.15	0.91	TES-LH
20	Isobutene	D-sorbitol	370.15	303.15	0.94	TES-LH
21	Butane	D-sorbitol	370.15	303.15	0.96	TES-LH
22	Isobutane	D-sorbitol	370.15	303.15	0.97	TES-LH
23	Isopentane	Methyl fumarate	375.15	303.15	0.74	TES-LH
24	Pentane	Methyl fumarate	375.15	303.15	0.74	TES-LH
25	Butene	Methyl fumarate	375.15	303.15	0.75	TES-LH
26	Isobutene	Methyl fumarate	375.15	303.15	0.78	TES-LH
27	Butane	Methyl fumarate	375.15	303.15	0.80	TES-LH

Table 5. Cont.

No	Working Fluid	PCM	T ₂ (K)	T ₄ (K)	$\zeta(T_2)$ (-)	Process
28	Isobutane	Methyl fumarate	375.15	303.15	0.81	TES-LH
29	Isobutane	Methyl fumarate	375.15	303.15	0.85	TES-EVA
30	Isobutene	Methyl fumarate	375.15	303.15	0.99	TES-EVA
31	Isopentane	Catechol	377.45	303.15	0.89	TES-LH
32	Pentane	Catechol	377.45	303.15	0.90	TES-LH
33	Butene	Catechol	377.45	303.15	0.91	TES-LH
34	Isobutene	Catechol	377.45	303.15	0.94	TES-LH
35	Isobutane	Catechol	377.45	303.15	0.96	TES-EVA
36	Butane	Catechol	377.45	303.15	0.97	TES-LH
37	Isobutane	Catechol	377.45	303.15	0.98	TES-LH
38	Isobutane	Quinone	388.15	303.15	0.98	TES-EVA
39	Isobutane	MgCl ₂ ·6H ₂ O	390.15	303.15	0.95	TES-EVA
40	Isobutane	Succinic anhydride	392.15	303.15	0.75	TES-EVA
41	Isobutene	Succinic anhydride	392.15	303.15	0.96	TES-EVA
42	Butene	Succinic anhydride	392.15	303.15	0.99	TES-EVA
43	Isobutane	Erythritol	393.15	303.15	0.44	TES-EVA
44	Isobutene	Erythritol	393.15	303.15	0.56	TES-EVA
45	Butene	Erythritol	393.15	303.15	0.58	TES-EVA
46	Butane	Erythritol	393.15	303.15	0.62	TES-EVA
47	Isopentane	Erythritol	393.15	303.15	0.67	TES-LH
48	Pentane	Erythritol	393.15	303.15	0.68	TES-LH
49	Butene	Erythritol	393.15	303.15	0.70	TES-LH
50	Isobutene	Erythritol	393.15	303.15	0.72	TES-LH
51	Isopentane	Erythritol	393.15	303.15	0.73	TES-EVA
52	Butane	Erythritol	393.15	303.15	0.73	TES-LH
53	Isobutane	Erythritol	393.15	303.15	0.76	TES-LH
54	Pentane	Erythritol	393.15	303.15	0.79	TES-EVA
55	Isobutane	Benzoic acid	394.15	303.15	1.00	TES-EVA
56	Isobutane	Stibene	397.15	303.15	0.79	TES-EVA
57	Isobutane	Benzamide	400.35	303.15	0.68	TES-EVA
58	Isobutene	Benzamide	400.35	303.15	0.99	TES-EVA
59	Isobutene	67% KNO ₃ + 33% LiNO ₃	406.15	303.15	0.84	TES-EVA
60	Butene	67% KNO ₃ + 33% LiNO ₃	406.15	303.15	0.89	TES-EVA
61	Isobutene	Polyethylene	408.15	303.15	0.66	TES-EVA
62	Butene	Polyethylene	408.15	303.15	0.71	TES-EVA
63	Butane	Polyethylene	408.15	303.15	0.83	TES-EVA
64	Isobutene	Phenacetin	410.15	303.15	0.89	TES-EVA
65	Butene	Phenacetin	410.15	303.15	0.96	TES-EVA
66	Butane	Acetyl-p-toludene	419.15	303.15	0.61	TES-EVA
67	Isopentane	Salicylic acid	423.15	303.15	0.88	TES-EVA
68	Isopentane	O-Mannitol	439.15	303.15	0.53	TES-EVA
69	Pentane	O-Mannitol	439.15	303.15	0.64	TES-EVA
70	Isopentane	D-Mannitol	440.15	303.15	0.48	TES-EVA
71	Pentane	D-Mannitol	440.15	303.15	0.59	TES-EVA
72	Isopentane	Hydroquinone	445.55	303.15	0.52	TES-EVA
73	Pentane	Hydroquinone	445.55	303.15	0.66	TES-EVA
74	Pentane	p-Aminobenzoic acid	460.15	303.15	0.78	TES-EVA
75	Pentane	Galactitol	461.15	303.15	0.32	TES-EVA

Table 5 lists 75 possible heat exchanger-TES device configurations (i.e., TES-EVA and TES-LH) utilizing selected PCM and working fluid to obtained dimensionless storage mass parameter less than 1 ($\zeta(T_2) < 1$). From 29 provided PCM in Table 2, only 20 selected PCM can perform $\zeta(T_2) < 1$, such as Mg(NO₃)₂·6H₂O, Xylitol, D-sorbitol, Methyl fumarate, Catechol, Quinone, MgCl₂·6H₂O, Succinic anhydride, Erythritol, Benzoic acid, Stibene, Benzamide, 67% KNO₃ + 33% LiNO₃, Polyethylene, Phenacetin, Acetyl-p-toludene, Salicylic acid, O-Mannitol, D-Mannitol, Hydroquinone, p-Aminobenzoic acid, and Galactitol.

Among these combinations, Erythritol as PCM applied for TES-LH or TES-EVA in the ORC system appears to be promising as there are 12 possible combinations with $\zeta(T_2) < 1$. Then, it is followed by Xylitol, Methyl fumarate, $\text{Mg}(\text{NO}_3)_2 \cdot 6\text{H}_2\text{O}$, Catechol, and D-sorbitol as PCM with 9, 8, 7, 7, and 6 combinations, respectively. Furthermore, the rest of the PCM listed in Table 5 has up to three combinations maximum either for TES-LH or TES-EVA.

Table 5 shows that the more combinations of working fluids with one kind of PCM, the more promising this PCM is to be used in TES-EVA or TES-LH. In that case, Erythritol pairing with selected working fluids, such as Butane, Butene, Pentane, Isobutane, Isobutene, and Isopentane seems to be a good option here as it can be used for both TES-LH and TES-EVA. In contrast, p-Aminobenzoic acid and galactitol as PCM pairing with Pentane in Table 5 apply solely to TES-EVA. Therefore, if TES-LH using Pentane is necessary to be installed, engineers or scientists have to find other suitable PCM or TES materials with $\zeta(T_2) < 1$ to have smaller devices.

5. Conclusions

The findings of a modelling analysis on sizing TES evaporator and liquid heater for ORC system with chosen HCs as working fluids and certain PCM as TES materials were provided in this study. The $\zeta(T)$ parameter was defined and computed for different ranges of heat source temperatures. The $\zeta(T)$ parameter characteristics may be used to estimate the size of the TES as well as the evaporator and liquid heater in an ORC system. This parameter may be used to calculate the size of TES for various low-boiling working fluids and thermal energy storage materials. The modelling findings show that for the selected modelling conditions (i.e., cycle operating temperature range, pairs of low-boiling working fluids, and PCMs), the $\zeta(T)$ parameter was ranging from 0.32 to 4.14. The results also reveal that changing evaporator temperature has a significant effect on the TES sizing parameter in ORC as the enthalpy change of the evaporator and liquid heater varies. According to the findings, it is recommended to consider PCM as a TES material in cases for which the value of a $\zeta(T)$ parameter is less than one. The rationale for this is that the lower value of $\zeta(T)$ parameter enables the possibility of design and implementation of a more compact and lighter evaporator and liquid heater, which is considered to be applied and implemented in a planned or existing ORC system.

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Nomenclatures

c	Specific heat capacity (J/kg·K)
h	Specific enthalpy (J/kg)
m	Mass (kg)
$\dot{m}$	Mass flow rate (kg/s)
P	Power (Watt)
$\dot{Q}$	Heat transfer rate (Watt)
T	Temperature (K)
V	Volume (m^3)

Greeks:

η	Efficiency (-)
ρ	Density (kg/m ³)
θ	Liquid fraction (-)
λ	Solid fraction (-)
ζ	Dimensionless storage mass parameter (-)
Subscripts:	
a,b,c,0,1,2,3,4	process in the cycle
CDS	Condenser
env	Environment
EXR	Expander
HE	Heat exchanger
hs	Heat sources
is	Isentropic process
l	Liquid phase
LH	Liquid heater
PMP	Pump
re	Real process
s	Solid phase
wf	Working fluids
Abbreviations:	
CFC	Chlorofluorocarbon
GWP	Global warming potential
HC	Hydrocarbon
HCFC	Hydrochlorofluorocarbon
LNG	Liquefied natural gas
ODP	Ozone depletion potential
ORC	Organic Rankine cycle
PCM	Phase change material
TES	Thermal energy storage

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