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Integration of Thermal Energy Storage Systems and Thermodynamic Analysis of Solar Combined Power Plants

Ghaith Thaaer Fadhil Al-Doori, [a, †] Falah Mohammed Abed [b, ‡], Hayder Subhi Faisal [c]

[a,b] Al-Dour technical Institute -Northern Technical University, Iraq

[c] College of Health and Medical Techniques/Al-Dour - Northern Technical University, Iraq

[†] Present address: Al-Dour technical Institute-Northern Technical University, Iraq

[‡] **Corresponding author**: ghaith.tf@ntu.edu.iq

Abstract

This research paper examines Thermal Energy Storage (TES) systems and Solar Combined Power Plants (SCPP) thermodynamics. Solar concentrated power plants (SCPPs) need thermal energy storage (TES) devices to store and use peak solar energy. The research emphasizes finding an appropriate storage media, building the system to minimize energy losses, and optimizing operational parameters for efficiency and reliability. Also discussed is using simulations and mathematical models to determine the best system design and functioning. The paper emphasizes the necessity of thermodynamic analysis in developing thermal energy storage (TES) systems for supercritical carbon dioxide power plants. Solar combined power plants (SCPPs) with thermal energy storage (TES) technologies benefit the energy sector and society. Some key findings are listed below: Thermal Energy Storage (TES) devices let Solar Concentrating Power Plants (SCPPs) maintain output despite solar radiation changes to maximize energy efficiency. Plant efficiency increases grid dependability and reduces emergency power needs. Thermal Energy Storage (TES) devices allow sun Concentrated Power Plants (SCPPs) to generate power even under low sun irradiation. This technology improves renewable energy integration and use. Additional renewable energy sources will reduce fossil fuel use. TES systems improve energy reliability and consistency, reducing power outages. Savings: TES systems can reduce energy production costs by improving power plant efficiency and reducing backup power use. Environmental benefits: Thermal Energy Storage (TES) devices in Stationary Combined Power Plants (SCPPs) promote renewable energy and reduce fossil fuel backup power, reducing greenhouse gas emissions. The study prototype has a heat storage temperature range of 75–91 degrees Celsius and a discharge power range of 200–650 watts. Energy can be stored at 1 kilojoule per kilogram in the energy storage system. Comparing the results to published data shows that the system performs well in energy density and efficiency. The newly discovered mechanism retains five times more energy than water at 45 degrees Celsius. A recent design evaluation suggests that the system could benefit from a more precise design and higher-quality materials. In view of various circumstances, Thermal Energy Storage (TES) systems and Supercritical Carbon Dioxide Power Plants may be needed to provide a future with reliable and ecologically benign energy sources.

Keywords- Thermal Energy Storage, Solar Combined Power Plant, Environmental Benefits, Storage Medium, Thermodynamic Analysis.

I. INTRODUCTION

Energy production is the fulcrum of economical, scientific, and social development worldwide. However, economic crisis, instability in the price of oil and gas, a difficult geo-political situation and a growing environmental conscience have favored a massive introduction and development of renewable energy sources, clean, worldwide available, and inexhaustible as mentioned in [1]. Moreover, energy efficiency has become an important target since energy savings and high-efficiency systems represent a fundamental part in the development towards a more sustainable and cleaner world as mentioned in [2]. Global energy policies reflect such a situation, both in the Western and Eastern countries. Indeed, production of energy from renewable sources represents a consistent share in the energy mix of most countries, including some emergent countries and, surprisingly, the majority of South American and African countries, as shown in Figure 1 Trend is towards an increase of installed capacity of systems employing renewable energy sources, as shown in Figure 2 for the solar thermal case.

Such a situation is also boosted by support policies promoted by governments for both privates and industries, in order to sustain the production, R&D and commercial diffusion of such systems. In fact, as to 2023, 144 countries have defined renewable energy targets and developed energy policies aimed at efficiency as mentioned in [3]. European Union has indicated the notorious 2030 targets as given in [4]:

- 20% reduction of greenhouse gaseous emissions;
- 20% of renewables share;
- 20% increasing of energy efficiency.

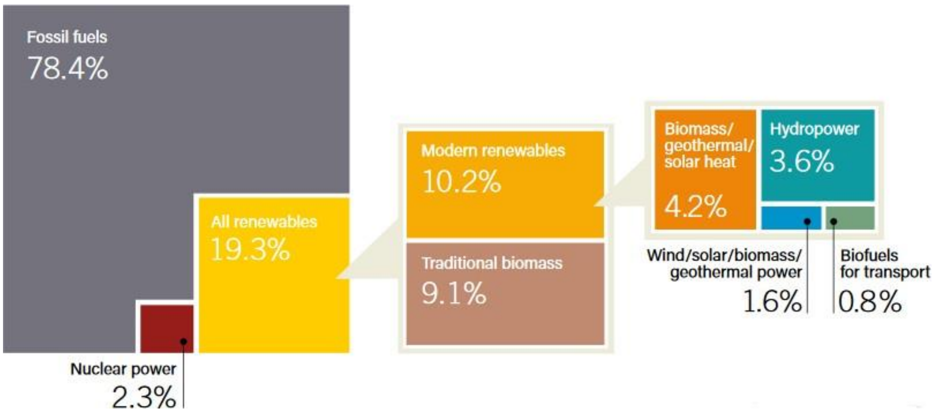

Figure 1. Share of renewables worldwide. Source: IEA

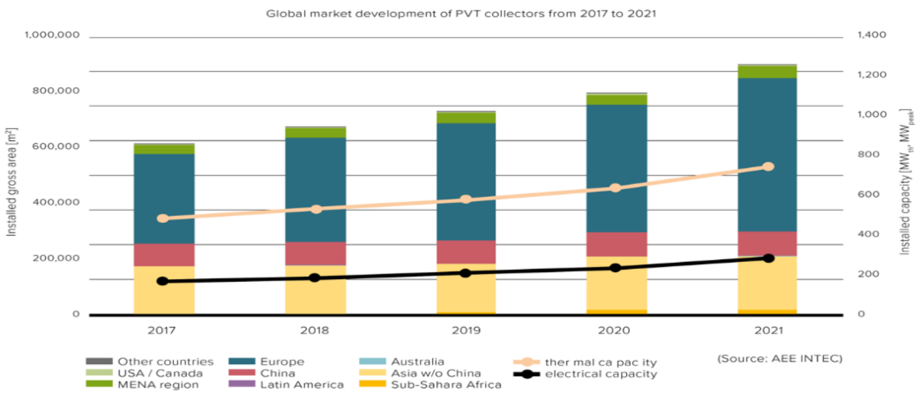

Figure 2. Global solar thermal capacity installed in the last years [5].

Energy efficiency and reduction in CO2 emissions, however, are linked not only to renewable energies, but also to waste heat recovery. Considering as an example the transportation sector, a total of about 450 k/tons of CO2 per year emissions can be estimated, half of which could be reduced by reducing the fuel needed for propulsion, mainly thanks to waste heat recovery as mentioned in [6]. In such a context is hence clear that, in the next future, there would be an increasing and urgent need for architectures built for energy efficiency, in the residential, industrial and mobility fields as mentioned in [7]. Key component for a system created for efficiency enhancement is a thermal storage, to cover for the gap between heat generation and heat demand and to effectively distribute it through the various users.

A. Benefits of Using a Thermal Storage

The utilization of thermal energy storage in various fields has long been established [8, 9] , not only in residential applications, but also in district heating as mentioned in [10] and in commercial and industrial ones as mentioned in [11]. The main advantages deriving from the application of a thermal storage system can be summarized as follows:

1. decoupling of the time between availability of a thermal source and its request.
2. better exploitation of energy, due to the possibility of producing and storing energy when the cost is lower.
3. reduction of peak demand, allowing energy providers to reduce the costs related to energy production and to increase the efficiency of generation.
4. reduction of CO2 emissions.
5. possibility to size energy generation and distribution equipment for a lower power, with significant cost benefits.

B. Aim of Study

The present thesis deals with thermal storage technologies, with special focus on heat storage from solar radiation and waste heat recovery (e.g. from industrial processes and internal combustion engines) as mentioned in [12]. The main objective of the thesis are the development and experimental testing of thermal energy storage systems suitable for low-grade waste heat applications (T <100°C). The design of the systems will be described, and the experimental measurements presented. Through the experimental benchmarking of the realized systems, some considerations and optimization regarding the actual application of them under real boundaries will be discussed. The simulation of such a scenario indicates that, not only is possible to achieve the target proposed, but also at a cost for heating/cooling 15% lower than current alternatives. Moreover, the new generation district heating networks should be designed for high efficiency at low temperatures and peak shaving, objectives that can be fully satisfied only with the integration of thermal storage systems for DHW and the heating substations. Finally, a quantitative comparison between the technologies will be proposed, serving also a starting point for the definition of future standards.

The objectives of thermodynamic analysis of thermal energy storage (TES) systems integrated with a solar combined power plant (SCPP) include:

1. Selecting the appropriate storage medium: The objective is to select a storage medium that has a high specific heat capacity, low cost, and availability to ensure maximum efficiency and cost-effectiveness using EES software.
2. Designing an efficient TES system: The objective is to design the TES system to minimize energy losses during storage and retrieval, considering the effects of thermal cycling and material fatigue.
3. Optimizing operating parameters: The objective is to determine the optimal operating parameters, such as charging and discharging rates, to maximize energy efficiency and reliability.

Overall, the objectives of thermodynamic analysis are to improve the efficiency, reliability, and cost-effectiveness of TES systems integrated with SCPPs and to contribute to the development of a more sustainable and reliable energy future.

II. LITERATURE REVIEW

Thermal Energy Storage (TES) is the whole assembly of technologies allowing for heat or cold energy to be used at a different time from generation. The basic flow diagram for a thermal energy storage process is shown in Figure 3: when excess hot or cold energy is available, this is used to charge the storage. When a demand for such energy exists, the storage is discharged as mentioned in [13]. The storage period in between can vary from a few hours to months.

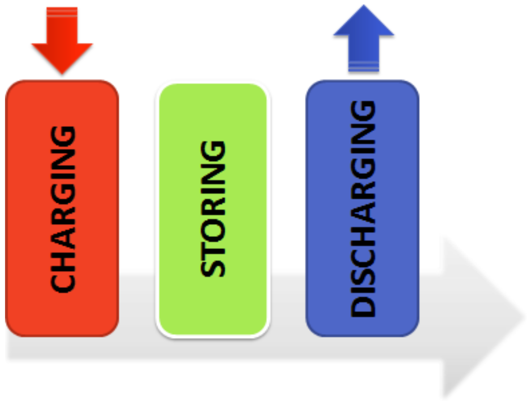

Figure 3. Flow diagram of a thermal energy storage process.

A general classification of the methods for thermal energy storage which will be further analyzed in the following sections, is given in Figure 4 [14]. A qualitative comparison between the various storage technologies, based on the different energy density levels achievable with the above-mentioned technologies is shown below:

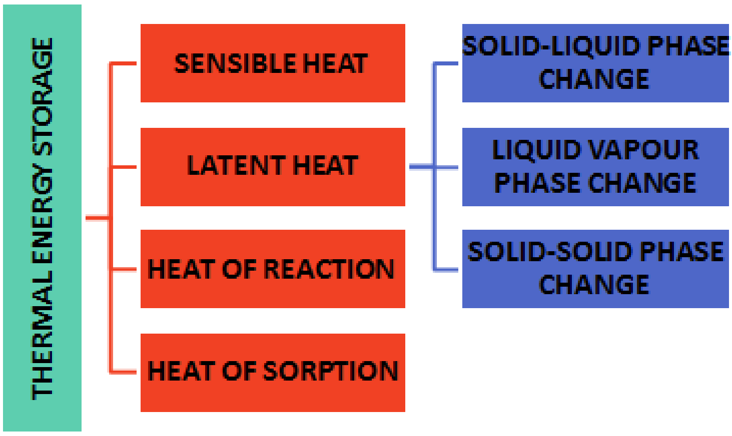

Figure 4. Classification of thermal storage methods.

Figure 5 It clearly shows that, starting from traditional sensible heat storage to the most efficient methods employing physical or chemical processes, the density enhancement can reach a ratio up to 8 [15]. The same concept is depicted in Figure 6, where volume needed to store 1850 kWh (with consideration of 25 % heat losses, based on a 70°C temperature increase for water) is shown in [16].

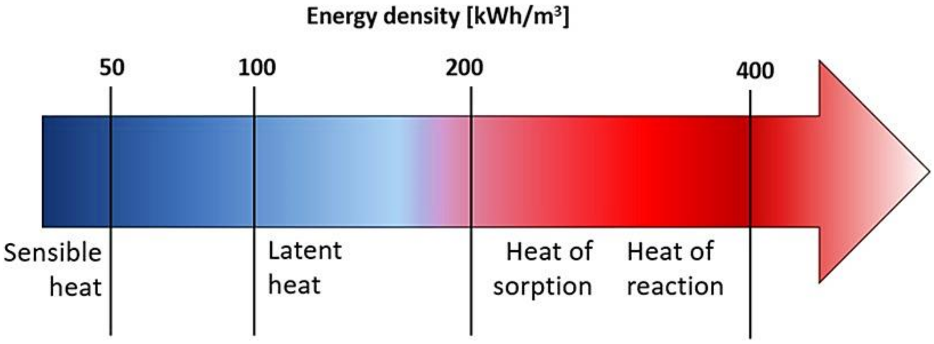

Figure 5. Energy density level for the different thermal storage technologies [16].

Sensible heat is the traditional methods used for storing energy. It is based on the increment in temperature of a storage medium when this is heated. The energy stored is linked to the temperature by a direct proportionality, as shown in Figure 6. The amount of energy stored can be expressed through an equation of the type:

$$\Delta Q = mc_p \Delta T \quad (1)$$

With m the mass of the storage medium and cp its specific heat. Different heat storage materials can be applied for this type of storage, both in solid and liquid form, as summarized in Table 1 [17].

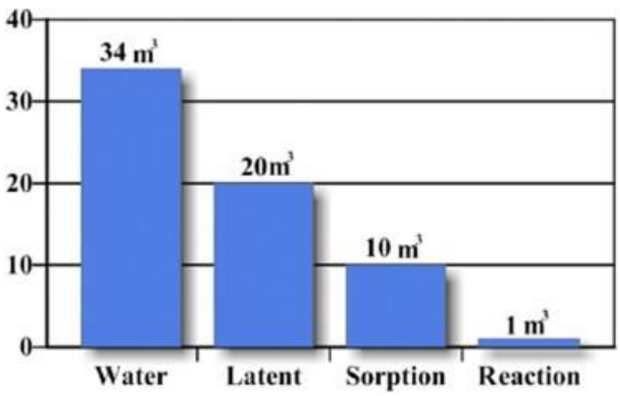

Figure 6. Volume needed to store 1850 kWh, comparison among technologies [18].

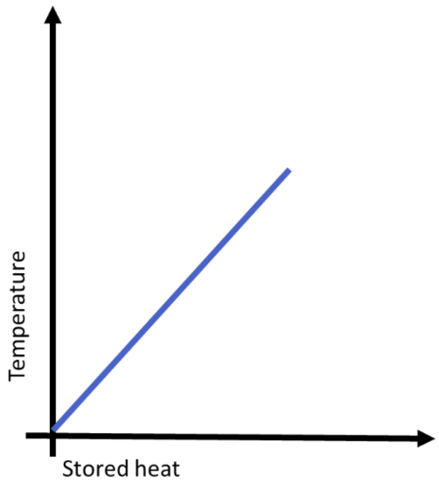

Figure 7. Energy as a function of temperature, sensible heat.

The temperature range covered by such materials is very high, from 0°C to 400°C. The advantage of liquid materials over solid ones is that active storage can be applied (without the need of a heat exchanger) and in general they require a simpler and cheaper storage design, because of the higher heat transfer efficiency as mentioned in [19]. On the contrary, solid materials do not have problems related to vapor pressure and the formation of possibly corrosive or explosives compounds and are in general very cheap. Since some of them are traditional construction materials, their implementation for the thermoregulation of buildings is easy as mentioned in [20]. Their low thermal conductivity requires high contact area with the heat transfer fluid (HTF).

Latent heat systems allow to accumulate energy by means of a phase change —mainly the solid-liquid one— as shown in Figure 2.6 as mentioned in [21]. Indeed, phase changes are associated to absorption or cession of energy at constant temperature. In this case, stored energy can be defined as:

$$\Delta Q = \Delta H \quad (2)$$

Where the ΔH is the enthalpy associated to the phase change. In case of the solid-liquid phase change:

$$\Delta H = \lambda_m \quad (3)$$

With λm being the latent heat of fusion/solidification. If phase change is completed, further energy is stored in the form of sensible heat and therefore, for a material starting in solid form at an initial temperature T0 and heated to a final temperature Tfin, superior than melting temperature, the total amount of heat storable is given by [22]:

Materials usually employed for TES with latent heat are called phase change materials or PCMs. The main advantages deriving from the utilization of latent heat, if compared to other technologies, are:

- higher energy density than sensible heat media.
- dependence of thermal behavior from phase change temperature, a feature allowing to tailor the material according to the specific application to be realized. [23, 24].

Chemical reactions can be used for heat storage/release, since between the reactants and the products of a chemical reaction there is a different enthalpy content, which is the so- called heat of reaction. When there is an exothermic reaction, heat will be released to the environment, while an endothermic reaction will allow storing heat [25].

III. METHODOLOGY

In this session, the whole process of development of a thermal energy storage using a phase change material as the storage medium will be reported. The approach followed in the description of the activity is focused at highlighting the progress with respect to the state-of-art. Accordingly, after a short description of the main features of the system, the recent developments regarding the specific application will be drawn. After the overall presentation of the activity carried out, the main outcomes will be summarized. The main boundaries of the project and the target characteristics required to the storage are:

a. Temperature of the heat source in the range 80°C-100°C;
b. Temperature of the heat to be supplied to the user in the range 65-70°C;
c. Energy density higher than 100 MJ/m3.

This is consistent with charging through non-concentrating solar collectors and discharging in a temperature range suitable for Domestic Hot Water (DHW) production or driving of thermal chillers/heat pumps. The methodology followed in the development of the system is summarized in Figure 8. In particular, the choice of the storage material was realized starting from an experimental campaign carried out using EES software. Once the best performing material was identified, a first design of the system was proposed, following the criteria reported . Since not much data is available in literature on prototypal systems based on latent heat storage in the temperature range identified, it was decided to follow a double approach: on the one hand, a custom-made system based on fin-and-tubes configuration was realized; on the other hand, an asymmetric plate heat exchanger chosen among commercial ones was tested and compared to the former configuration. Both systems were experimentally characterized using a testing rig at EES Software, that was specifically adapted for the testing of hybrid and latent heat storages with charging temperatures up to 100°C. The results of the experimental benchmarking were used for a critical review of the design of the system and propose an optimization. In order to accomplish such a goal, a simplified model was developed in COMSOL Multi-physics, suitable for the definition of an improved design of the system and validated with the experimental measurements.

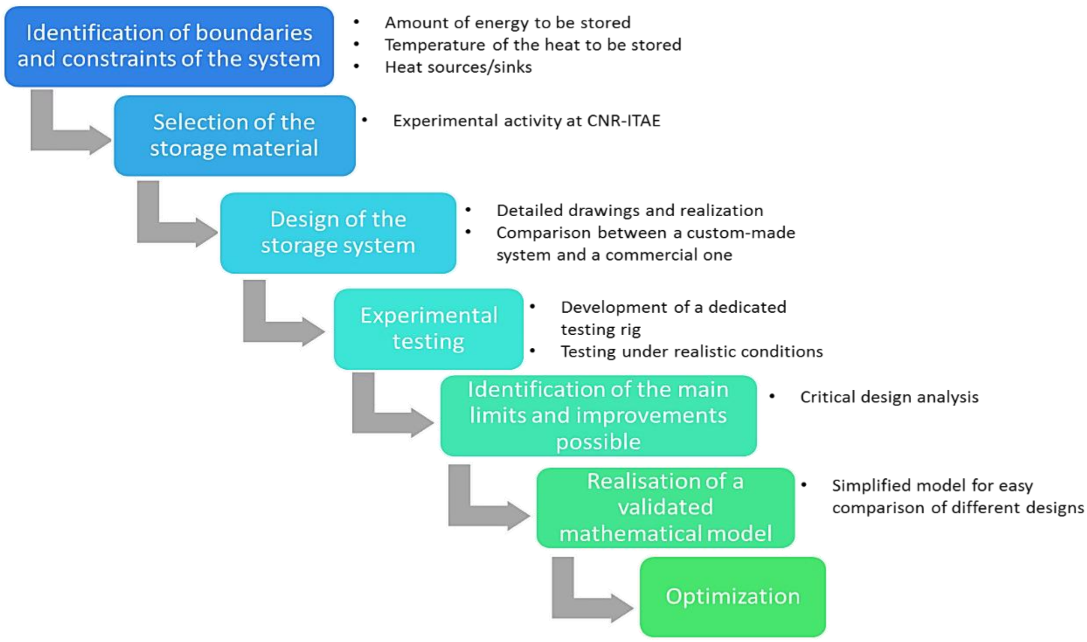

Figure 8. Methodology followed in the development of a latent heat storage system.

A. Designing the Thermodynamics System

The issues related to the design of a latent heat storage system are summarized and are schematically reported in Figure 9. It is possible to distinguish three different levels before the final realization and application of a latent thermal energy storage (EES): a first screening must be made regarding the materials available and their practical application, that can be limited by problems such as the cycling stability, degradation, sub-cooling and so on. In addition, as already discussed, heat transfer inside a EES is often a critical issue and therefore both the design of the material and the component should take that into account. At the component level, the decisions on the layout of the system and its thermal insulation should be made. However, as for the case of the material and component level, an overlapping with the system level can be identified, mainly regarding the operation of the system (e.g., the possibility of simultaneous charge/discharge that influences the construction of the heat exchanger that is included in the storage). One aspect that is not commonly addressed is the analysis of the whole life cycle of the system, that should be instead regarded in the future, to be able to compare the operation of this type of storages with traditional sensible heat ones.

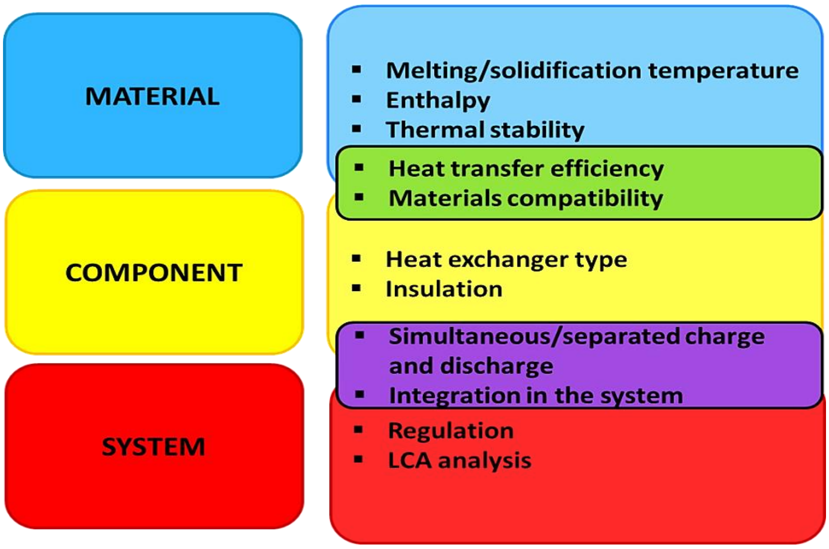

Figure 9. Design of a latent heat storage system.

The studies in literature regarding the application of phase change materials in systems with heat at 60°C-100°C mainly comprise the coupling with solar systems, either for domestic or industrial use. Within this field, different applications have been investigated:

A. systems for DHW production, with the storage embedded either in the solar collector or as a stand-alone component.

B. systems based on air solar collectors and PCM-based thermal storage for building heating applications.

C. non-concentrating solar thermal.

Several research for this application concentrates on energy analysis or numerical modelling. To support the heat rejection of the absorption cooling machine to the ambient, provides the energy analysis of a solar cooling plant utilizing a latent thermal storage on the medium temperature loop. Incorporating a latent heat storage into solar cooling plants fitted with absorption chillers, concentrate on energy, efficiency, and economic analyses. A comparison between a typical open wet tower and a PCM store installed in a solar cooling plant's heat rejection loop is made. The investigation, which intended to demonstrate the viability of the technical solution suggested, was carried out through system simulation in several zones around Spain.

Regarding the experimental works carried out on materials and components, most of them is focused on high temperature thermal storage for coupling with concentrating solar collectors (e.g., parabolic through, Fresnel collectors), a prototype is described, made up of a vertical spiral heat exchanger filled with paraffin wax having a melting temperature range around 80°C. Tests have been carried to analyses the solid-liquid transition, and natural convection occurring within the melting PCM was found to be a great parameter of influence on heat transfer dynamic. Outcome of the presented literature analysis is that, in the investigated temperature range

(60-100°C) further experimental work is needed towards the characterization of latent heat storage systems.

IV. RESULTS

The data presented in Figure 10 illustrates the cumulative energy measured and the power delivered to the storage throughout the charging procedure. Commencing at an initial pinnacle of approximately 12 kilowatts, the power gradually diminishes to an average level of approximately 2 kilowatts. Upon careful consideration of all pertinent criteria, it has been determined that the duration of the process amounts to approximately 85 minutes. The maximum amount of energy delivered is 6 megajoules (MJ), which is equivalent to 375 kilojoules per kilogram of phase change material (kJ/kgPCM).

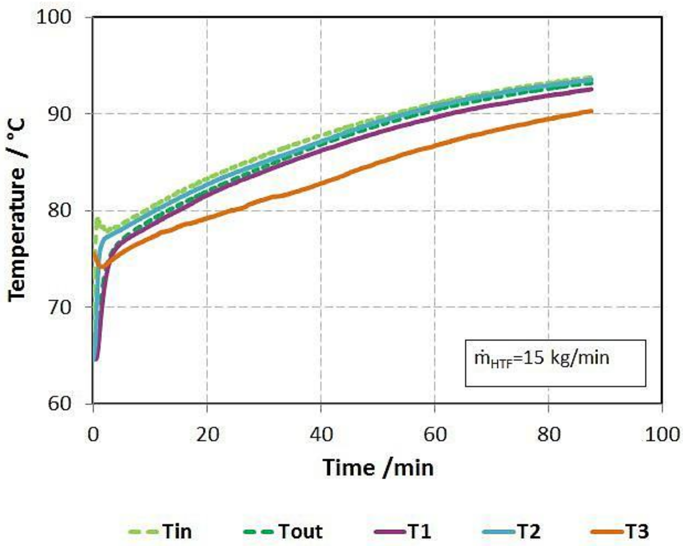

Figure 10: Temperatures during a charge with m. =15 kg/min, T0=65°C, Tfin=93°C.

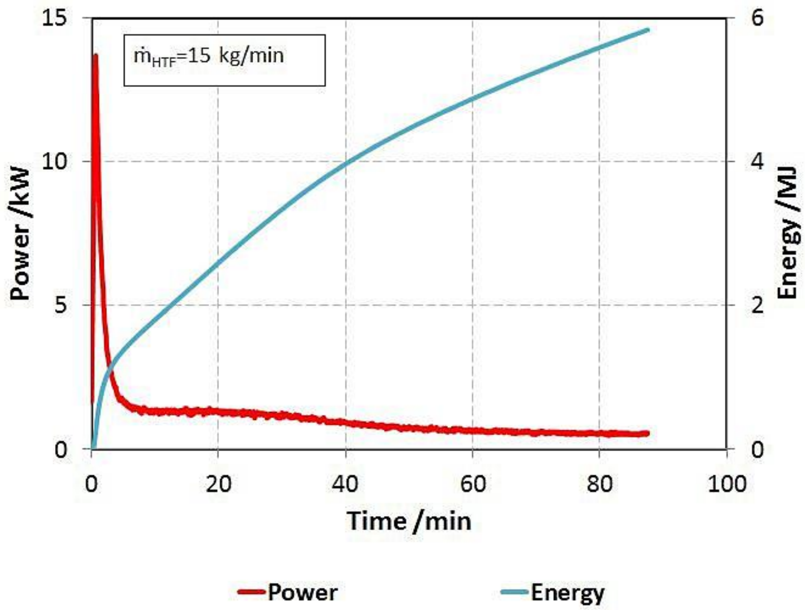

Figure 11. Power supplied and cumulative energy during a charge with m. =15 kg/min, T0=65°C, Tfin=93°C.

Figures 11 and 12 illustrate the relationship between the energy required for system charging and the corresponding efficiency, with respect to the flow rate. Three distinct test series are conducted, each characterized by a unique target temperature at the conclusion of the experiment, while commencing at an initial temperature of 70 degrees Celsius. The relationship between flow rate and energy consumption suggests that an increase in flow rate results in a decrease in energy requirements, hence enhancing overall efficiency. The augmentation of melting dynamics occurs when the flow rate of the system is heightened, hence facilitating improved heat conduction. The accelerated rate of melting facilitates reduced charging durations and minimized heat dissipation. A significant increase in efficiency of around 10% is observed when the flow rate increases from 10 to 25 kg/min, resulting in potential energy savings of up to 1 MJ. The efficiency of the fin-and-tubes heat exchanger (HEX) system has a range of 82 to 92% at lower flow rates, as shown from the recorded measurements. The lower numerical values are indicative of the situation when charging is exclusively conducted at the melting point. As the flow rate increases, the current efficiency of 93% exhibits reduced sensitivity to variations in the surrounding environment. This phenomenon can be attributed to the relatively stable duration of the charging process, which consequently minimizes heat losses. These heat losses are primarily responsible for the observed disparity between the delivered energy and the theoretically expected energy output. Greater consideration should be given to the heat transfer mechanism and the duration required for charging the system.

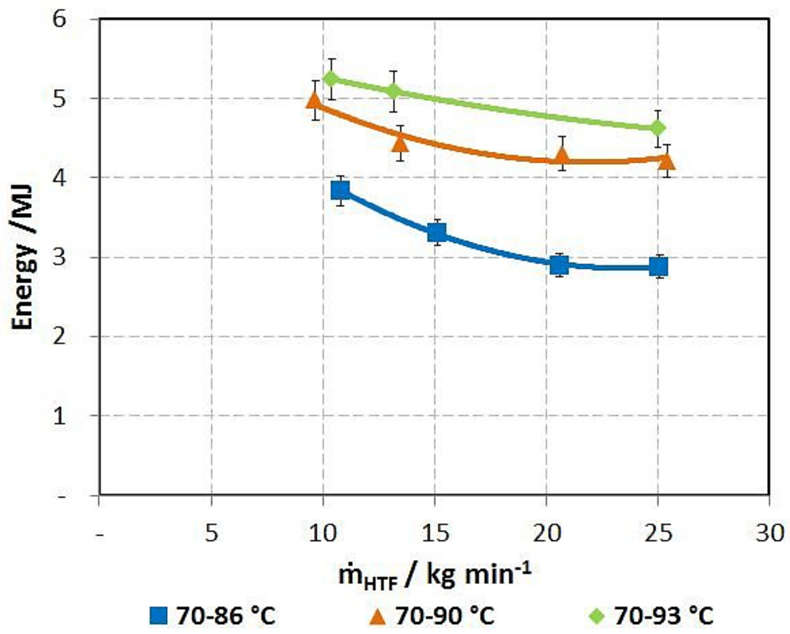

Figure 12. Effect of HTF flow rate on the energy supplied during charging tests starting from 70°C.

Figure 13 displays the energy provided and process efficiency for several charging experiments with varying HTF flow rate and beginning storage temperature. Starting from the melting onset temperature of 70°C, the energy must be provided is almost half that needed to charge the store from 25°C to 93°C, or 9 MJ, or 562 kJ/kg. When designing the storage, it is crucial to specify if the operation entails a complete cooling down of the system, up to ambient temperature, since this might have a significant impact on the system's actual performance relative to its rated performance. In solar-assisted systems used for DHW or heating, one instance where the temperature of the storage might drop considerably below the onset temperature of solidification occurs after nightfall (especially in colder climates). When calculating the performance and characteristics typical of the charge of the system in these situations, the sensible heat contribution in solid phase must be taken into account. The efficiency of the system rises when the storage's starting temperature rises because the impact of heat losses is reduced. Lastly, as was previously said, larger flow rates increase the system's efficiency. The efficiency rises by 5% for charges moving at 15 kilograms per minute between beginning temperatures of 25 and 70 degrees Celsius. This indicates that the main parameter to be considered, when analyzing different charges, is the initial temperature, followed by the flow rate of the HTF, rather than the efficiency. Table 3.8 reports, in addition to the energy and the efficiency for selected tests, also the average power during the test. It is possible to notice that the values are quite low (1.1 to 1.7 kW). It is interesting to notice that the average power decreases with increasing initial temperature of the storage. Indeed, a higher temperature difference between the HTF and the PCM means that a higher driving force for the melting temperature is available. Instead, with a reduced temperature difference the process becomes slower and a lower power is measured.

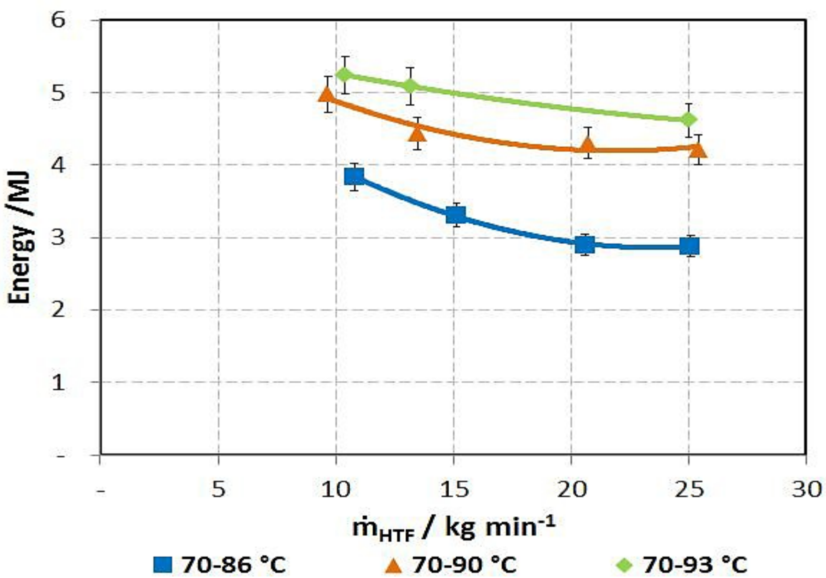

Figure 13. Effect of HTF flow rate on the efficiency during charging tests starting from 70°C.

The duration of charging and discharging is a critical factor in various applications, such as the integration of solar energy systems. Moreover, there are instances where achieving a complete charge is unattainable, such as when there is an inadequate supply of solar energy. An analysis of the system's behaviour in relation to the charging time would yield intriguing insights. This is achieved through the comparison of two samples that were initially maintained at a temperature of 70 degrees Celsius, but were subsequently heated to 86 and 93 degrees Celsius, respectively. The experimental trials conducted within the temperature range of 70 to 93 °C effectively utilize the sensible heat of the phase change material (PCM) in its liquid state. Conversely, the trials conducted between 70 and 86 °C solely focus on observing phase transitions. The objective of this study is to determine the duration required to reach the desired temperature across two distinct temperature ranges, as well as across various flow rates of the Heat Transfer Fluid (HTF). The ability to regulate the flow rate of the HTF enables the anticipation or adjustment of the system's charging duration based on process limitations, as the behaviour may be fully characterized by a second-order polynomial equation.

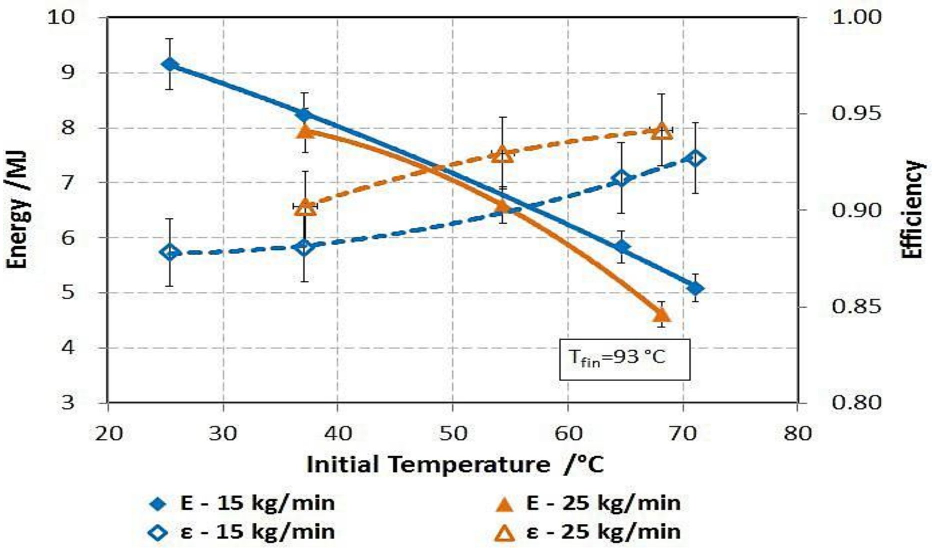

Figure 14. Energy and efficiency for various charging tests at different initial temperatures.

Figure 14 illustrates the duration required for the transfer of the remaining energy necessary to achieve complete system charging. Specifically, we examined the time required to accomplish 20%, 50%, 70%, 80%, 90%, and 95% of the whole expenditure. In Figure 4.6, the data is presented in a manner where the results are depicted as a function of the entire charge time, as opposed to the duration required to complete a particular subset of the charge. The significance of the time needed to achieve a steady state of charge is rooted in its independence from flow velocity and its dependence on the temperature boundaries within the system. Furthermore, during the experimentation conducted within the temperature range of 70 to 93 degrees Celsius, it was observed that the charging process reached a state of near completion within 60% of the entire time. The remaining duration was only attributed to the transfer of sensible heat, which occurred during the last phase of the test when the liquid phase change material (PCM) was subjected to heating. In order to elucidate the various processes involved, the data points exhibit a quadratic pattern throughout the entire progression, culminating in the final outcome.

Table 1. Energy supplied, efficiency and average power during selected charging tests.

Test	T_{fin}	**T0**	$\Delta T_{0\text{-}fin}$	$\dot{m}_{HTF}$	**E**	ε	P_{ave}
	°C	°C	°C	kg/min	MJ	-	kW
1	93	25	67	14	9.2	0.88	1.7
2	93	37	56	16	8.2	0.88	1.6
3	93	65	28	14	5.8	0.92	1.1
4	93	71	22	14	5.1	0.93	1.1
5	93	37	56	24	7.9	0.90	1.6
6	93	54	29	25	6.6	0.93	1.4
7	93	68	25	25	4.6	0.94	1.2

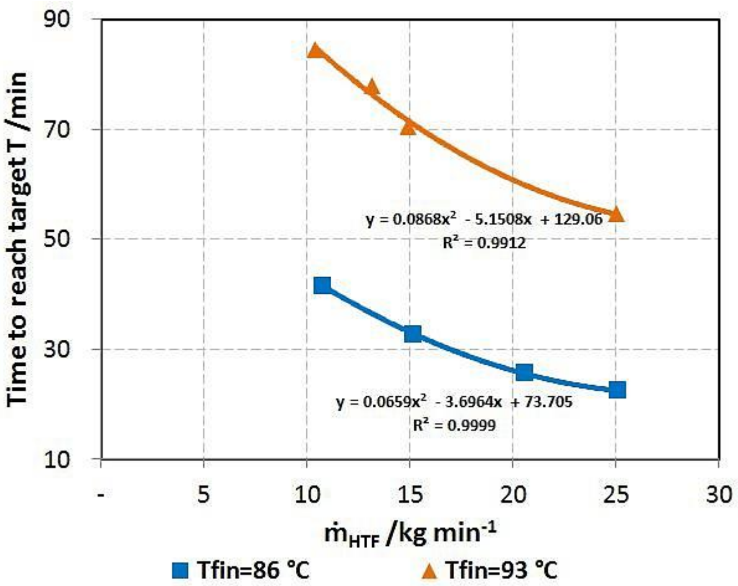

Figure 15. Time needed to reach target temperature as a function of the flow rate of HTF.

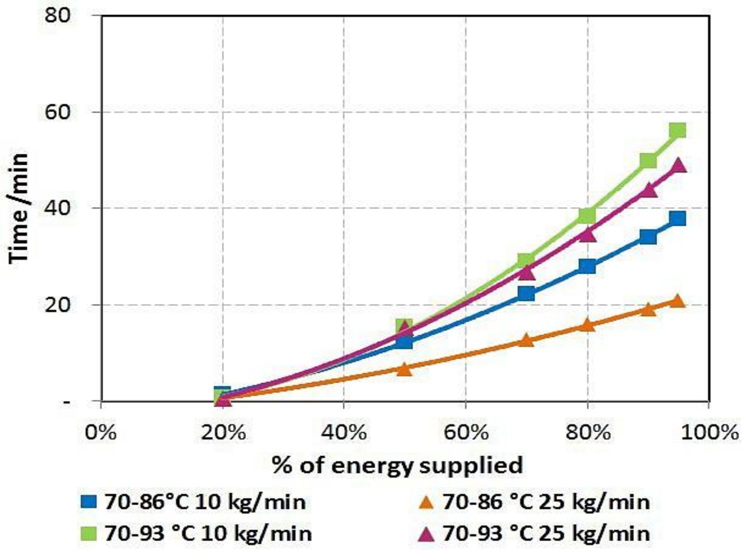

Figure 16. Time needed to transfer 20%, 50%, 70%, 80%, 90% and 95% of the total charging energy.

V. CONCLUSION

Thermal energy storage (TES) systems play a crucial role in solar power plants as they enable the storage and subsequent utilization of thermal energy generated during periods of maximum solar irradiation, hence compensating for lower sunlight availability. Energy can be stored in various Thermal Energy Storage (TES) systems, such as hot water, steam, molten salt, and other substances with a significant heat capacity. News has emerged regarding the development of a prototype for adsorption storage. The selection of AQSOA FAM Z02 was based on its thermodynamic analysis, which demonstrated superior desired characteristics over the whole range of temperatures examined. Subsequently, a storage system utilizing the material and a fin-and-tube heat exchanger was conceptualized and constructed. The device underwent rigorous testing at CNR-ITAE, an institution equipped with a specialized laboratory and testing apparatus for the evaluation of thermally powered chillers, heat pumps, and storages. The study investigated various operational modes, including Cold Storage, Daily Hot Storage, and Seasonal Hot Storage, and assessed the system's performance considering the influence of these modes and other relevant factors. The presented prototype has the capability to retain thermal energy within a temperature range of 2.3 MJ at 75 °C to 4 MJ at 91 °C. Furthermore, it exhibits an average power output ranging from 200 W to 650 W during the discharging phase. The findings demonstrate that the system demonstrates effective performance when evaluating both energy density and efficiency, as supported by the comparison with existing literature. At a temperature of 45 degrees Celsius, the recently identified system exhibits an energy storage capacity that is fivefold more than that of water. The examination of the system's architecture indicates that potential improvements can be made by using a more exact arrangement and utilizing components of higher quality.

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