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EXPERIMENTAL ANALYSIS OF LATENT THERMAL ENERGY STORAGE CHARGING AND DISCHARGING

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Summary

Experimental investigation of latent thermal energy storage (LTES) charging and discharging has been performed. The LTES unit is a shell-and tube type tank with water as the heat transfer fluid (HTF), which flows through the tubes, and technical grade paraffin RT 25 as the phase change material (PCM), filling the shell side. The total of 19 longitudinally finned tubes are arranged concentrically in the tank. A set of 30 thermocouples have been placed at various radial and axial positions on the PCM side for monitoring transient temperature variations during charging and discharging processes. Timewise temperature variations of PCM during charging and discharging, for different HTF inlet temperatures, have been presented. Stored and released thermal energy have been calculated and analyzed.

Key words: latent thermal energy storage, experimental research, charging and discharging.

1. Introduction

Due to increase in both global economy and population, the need for continuous energy supply has been steadily growing. Fossil fuels have been used as a principal energy source for most of the last century. However, these fuels emit compounds which are harmful to the environment and increase global warming. More sustainable technologies are needed to maintain both stable economic growth and healthier environment. One of the renewable technologies in domestic and industrial applications is the storage of thermal energy provided by solar radiation during the day, and its release during the night (Jegadheeswaran, 2009). Thermal energy can be stored in the form of sensible heat, latent heat or thermochemical energy. In a latent thermal energy storage (LTES), the thermal energy acquired by solar collectors is carried by heat transfer fluid (HTF) and stored inside a phase change material (PCM) during charging period (melting) and released during discharging period (solidification), using PCM’s latent heat to store and release additional energy. Since most organic PCMs exhibit low thermal conductivity (which is about 0.2 W/mK (Khan et al., 2016)), various heat transfer enhancement techniques have been suggested and investigated. The most common one is the use of extended surfaces (fins) and their geometry characteristics so placement inside the LTES can greatly increase heat transfer in both charging and discharging processes. Fins are implemented in various LTES geometries, e.g. double pipe, triplex tube and shell-and tube configurations, the latter of which is the most used (Al-Abidi et al., 2012).

Ezan et al. (2011) performed an experimental investigation of the thermal performance of shell and tube LTES during charging and discharging cycles with water as HTF. Storage capacity of the system was calculated for different operating and geometry conditions; HTF inlet temperature and flow rate, shell diameter and thermal conductivity of the tube material. It was concluded that the dominant heat transfer mechanism during melting is natural convection, and conduction during solidification. The effect of HTF inlet temperature on thermal performance is greater than the effect of HTF flow rate. Akgun et al. (2007) experimentally assessed charging and discharging processes in a vertical shell-and-tube heat exchanger. They observed that melting time was significantly decreased by increasing the HTF inlet temperature. Khan and Khan (2017) experimentally investigated the discharging cycles of paraffin in a shell-and-tube LTES with longitudinal fins. They studied the influence of HTF inlet temperature and flow rate. Increasing the HTF inlet temperature and flow rate

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resulted in lower thermal resistance caused by solidified paraffin. Hosseini et al. (2012) experimentally investigated the charging process in horizontal shell-and-tube LTES. They observed the highest temperature values are present in the uppermost region due to natural convection. Additionally, by increasing the HTF inlet temperature from 70 to 80 °C, the total melting time is reduced by 37%. Kabbara et al. (2016) experimentally investigated the discharging process of dodecanoic acid in a vertical shell-and-tube LTES with rectangular fins. They reported that discharge power was slightly improved by increasing the HTF flow rate. Lohrasbi et al. (2017) comparatively examined the thermal performance of PCM in vertical-shell-and-tube configurations with no fins, optimized circular fins and longitudinal fins. It was reported that the phase transition rate for optimized circular fins and longitudinal fins were 3.55 and 4.28 times higher as compared to no fins orientation, respectively. Agyenim et al. (2009) experimentally investigated the influence of radial and longitudinal fins on thermal performance in a shell-and-tube LTES with erythritol as PCM. It was reported that cumulative thermal energy discharge for no fins, radial fins and longitudinal fins were 4977.8 kJ, 7293.1 kJ and 8813.1 kJ, respectively. Similarly, Caron-Soupart et al. (2016) experimentally investigated the phase change behavior of paraffin RT 35 HC in shell-and-tube with three configurations: no fins, radial fins and longitudinal fins. They observed that longitudinal fins had resulted in greater temperature gradient and thermal power when compared to cases with radial fins or without fins. Agarwal and Sarviya (2016) designed and studied the shell-and-tube type LTES for solar dryer, with paraffin used as PCM, and air as HTF. Heat transfer characteristics of the system have been evaluated during charging and discharging processes. They studied the effects of flow rate and temperature of HTF on the charging and discharging process in LTES, obtaining temperature distributions along the radial and longitudinal directions. Thermal performance of the system was evaluated in terms of cumulative charged and discharged energy.

As seen from the literature, longitudinal fins are an effective means for enhancing thermal performance during both charging and discharging processes. This investigation presents an experimental analysis of charging and discharging processes in the shell-and-tube type LTES with external longitudinal fins. It aims to investigate the influence of HTF inlet temperature on charging and discharging processes. A series of measurements have been carried out in order to assess the LTES' thermal performance. Based on measurement data, stored and released thermal energy have been calculated. Results can be used in further investigations in modeling and optimization of heat transfer in LTES, as well as modeling and optimization of thermal systems which include this type of storage tanks.

2. Experimental setup

2.1. System description and LTES tank

Experimental setup consists of a LTES tank, 49 kW water-water heat pump, hot and cold water tanks, thermostatic mixing valve as well as circulation pumps in the condenser-hot tank circuit, evaporator-cold tank circuit and working tank-test unit circuit. Working tank is hot tank during charging, and cold tank during discharging processes investigations. The investigated LTES is designed and constructed shell-and-tube type tank, vertically oriented and consisted of 19 concentric aluminum tubes, each containing eight equidistant longitudinal fins with 66 mm length and 2 mm width, offset by an angle of 45°. The tubes are made of aluminum and their inner and outer diameters are 25 and 30 mm, respectively. Outer diameter of the tank is 950 mm, while its height is 1500 mm. To reduce heat losses through the shell, it has been insulated with 25 mm of expanded rubber foam. The LTES tank, tube configuration and single longitudinally finned tube are shown in Fig. 1.

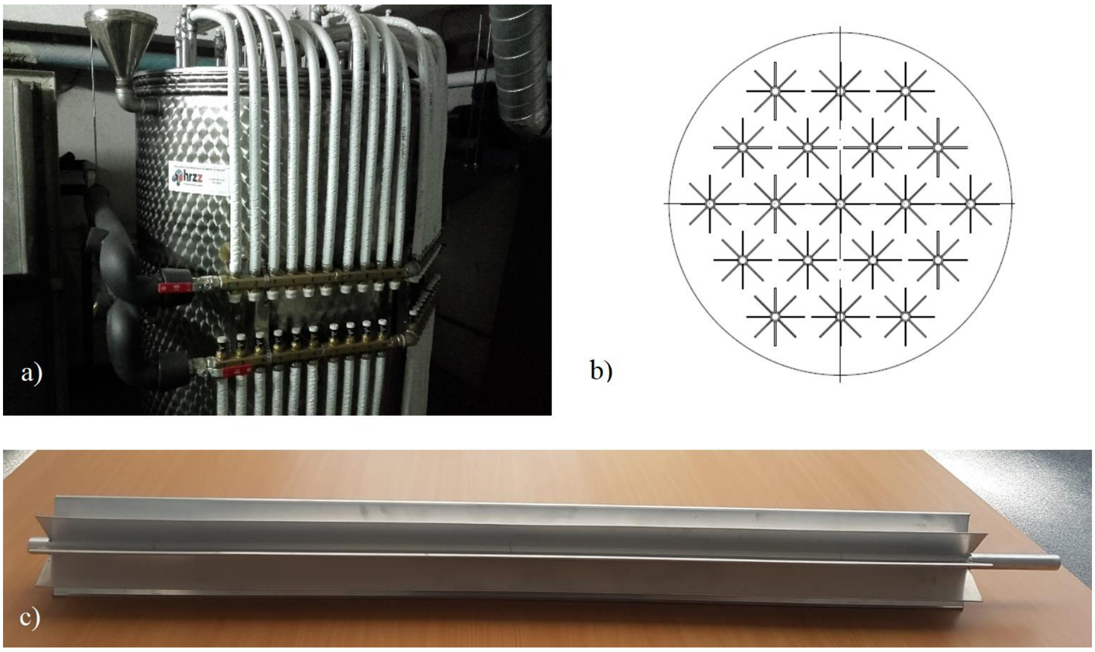


Fig. 1. Latent thermal energy storage tank (a), configuration of tubes and fins inside the tank (b), longitudinally finned tube (c)

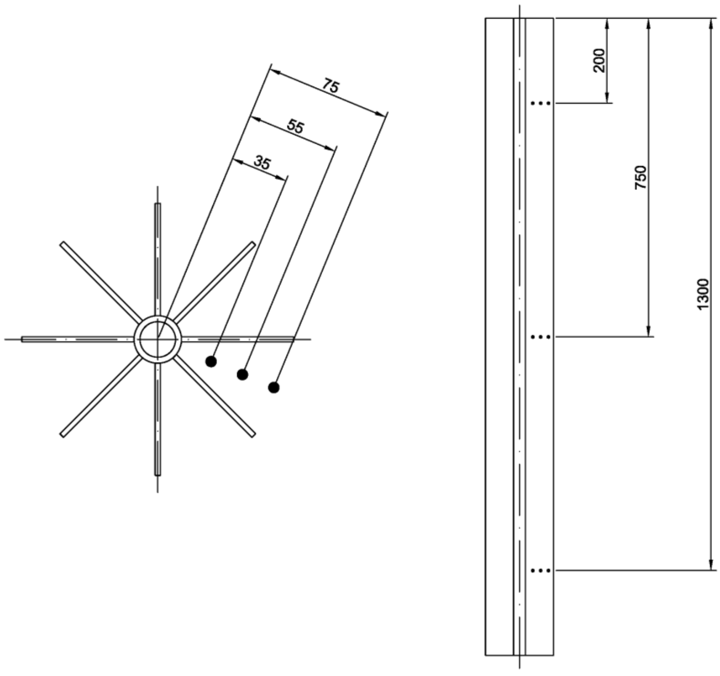
Water, which flows through the tubes, enters the tank at the top and serves as the heat transfer fluid. 760 kg of Rubitherm’s RT 25 paraffin is used as PCM and fills the shell side of the tank. Thermal and physical properties of RT 25 paraffin are given in Table 1.

Table 1. Thermal and physical properties of RT 25 (Rubitherm GmbH, 2018)

Melting/solidification temperature range	22-26 °C
Latent heat	170 kJ/kg
Thermal conductivity	0.2 W/mK
Specific heat capacity	2 kJ/kgK
Density solid/liquid	880/760 kg/m^3
Kinematic viscosity (liquid)	4.7 mm^2/s

2.2. Experimental procedure

Measurements have been performed in the Laboratory for thermal measurements at University of Rijeka, Faculty of Engineering. A total of 30 K-type thermocouples have been placed in PCM at axial and radial positions, in order to monitor the transient temperature changes during charging and discharging processes. Their axial and radial positions, around one tube in the tube arrangement, regarding to the water inlet position and tube center, are shown in Fig. 2 in top and cross section views, and in Table 2, where nomenclature of the thermocouples has been provided. Two additional thermocouples have been placed at the HTF inlet and outlet of the LTES.



a) b)

Fig. 2. Thermocouples position on the paraffin-side of the LTES, top view (a), cross section view (b)

Table 2. Axial and radial positions of thermocouples inside the LTES

Thermocouple no.	1	2	3	4	5	6	7	8	9
Axial position (m)	0.2	0.2	0.2	0.75	0.75	0.75	1.3	1.3	1.3
Radial position (m)	0.035	0.055	0.075	0.035	0.055	0.075	0.035	0.055	0.075

Data acquisition system, linked with personal computer, and the software LabView were used to acquire and store measurements into a file (Fig. 3). Temperatures were measured and stored every 10 seconds. Initial conditions were defined by uniform temperature distribution throughout the PCM, below melting point in charging investigations, and above melting point in discharging investigations.

Fig. 3. Data acquisition system linked with personal computer

Mass flow rate of HTF was constant, controlled by working tank-test unit circulation pump. Constant HTF inlet temperature was controlled by three-way valve. Flow and temperature control system is shown in Fig. 4. When all thermocouples had shown temperatures above the melting point during charging analyses or below melting point for discharging analyses, the experiment was completed.

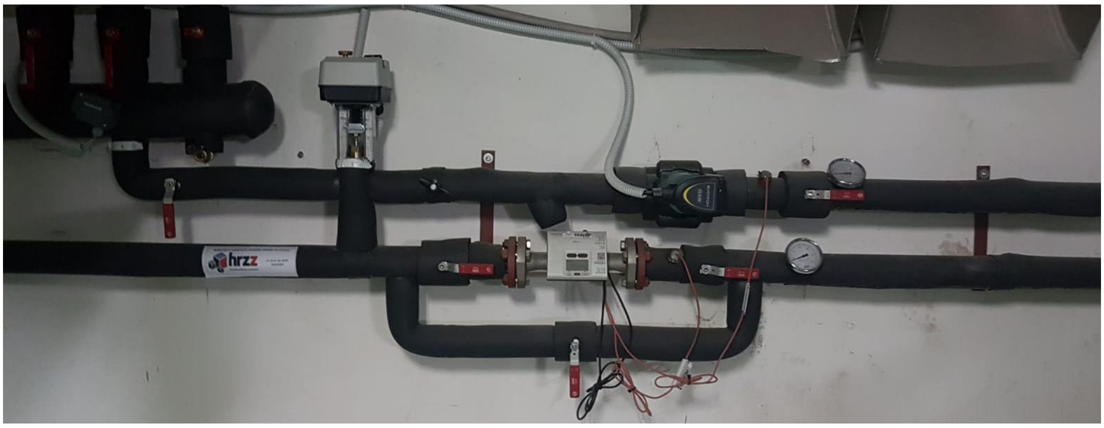


Fig. 4. Flow and temperature control system

3. Results and discussion

Temperature variations of PCM have been analyzed for various HTF inlet temperatures. In charging processes, the HTF inlet temperatures varied from 37 to 42 °C, and in discharging processes, those varied from 7 to 13 °C. Flow rate was 620 l/h for all analyzed cases, in both charging and discharging processes.

3.1. Charging processes

Transient PCM temperature variations in LTES, for different HTF inlet temperatures, during charging at axial position 0.75 m and radial position 0.035 m (position 4) are presented in Fig. 5. It can be noted that melting is not isothermal, and occurs in a temperature range, between 18 and 25 °C. This is due to natural convection-governed melting process. Conduction is dominant only in the solid phase, and as liquid layer of molten PCM grows, natural convection begins to take over as the dominant heat transfer mechanism. As the liquid layer grows, natural convection becomes more intense. As PCM is completely melted, i.e. when the temperature has reached 25 °C, a rise in temperature can be observed, indicating sensible heat transfer in completely molten liquid PCM, governed predominantly by natural convection. As seen from Fig. 5, shorter melting time is achieved for the HTF inlet temperatures 40 and 42 °C, while melting time for HTF inlet temperature 37 °C is considerably longer. Transient temperature variations of PCM for different radial positions at axial position 0.2 m (positions 1, 2 and 3) for HTF inlet temperature 37 °C are presented in Fig. 6.

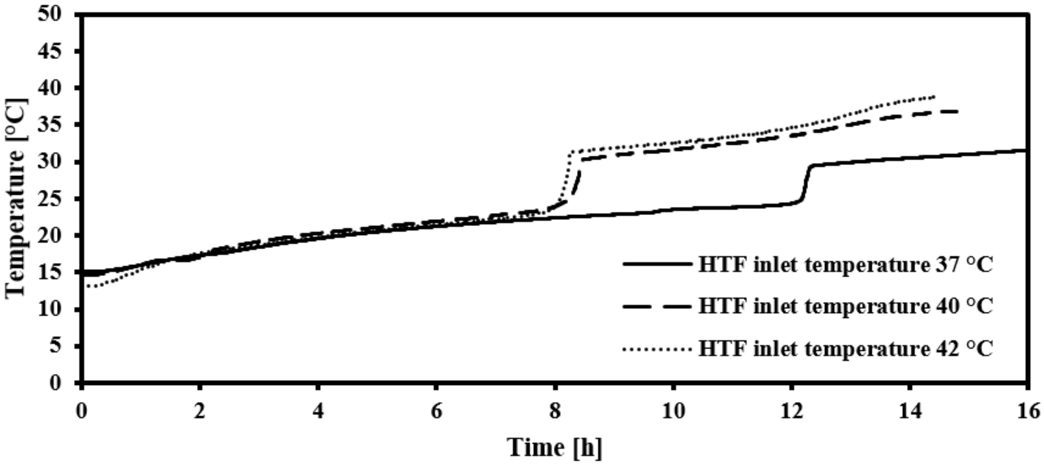


Fig. 5. Experimentally acquired transient PCM temperature variations inside the LTES at position x = 0.75 m, r = 0.035 m (position 4) during charging processes with different HTF inlet temperatures

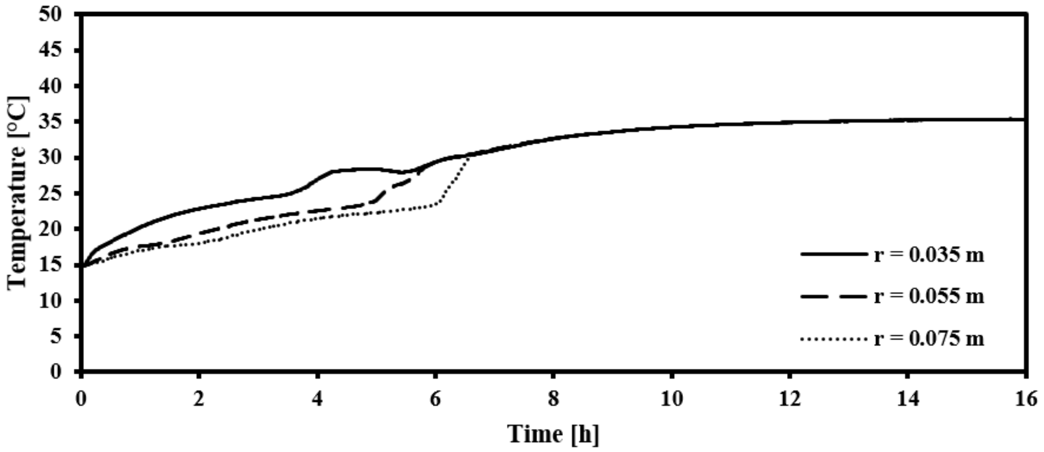


Fig. 6. Transient PCM temperature variations inside the LTES during charging with HTF inlet temperature 37 °C, at axial position x = 0.2 m and for different radial positions (positions 1, 2 and 3)

It can be observed that melting process is faster at smaller radius i.e. smaller distance from the tube. In comparison with Fig. 5, can be observed that melting process is significantly faster in the top-most section of the LTES (x = 0.2 m), due to rising of lighter liquid PCM particles, i.e. stronger influence of natural convection. Additionally, HTF temperature is the largest in that region, since HTF enters into the LTES at the top, also intensifying heat transfer.

3.2. Discharging processes

Transient PCM temperature variations in LTES, for different HTF inlet temperatures, during discharging at axial position 0.2 m and radial position 0.035 m (position 1) are presented in Fig. 7. It can be seen that, unlike melting processes, solidification processes are nearly isothermal, occurring at 25 °C. It is also observed that discharging process can be divided into three parts; cooling of liquid PCM, with natural convection present only at the beginning and diminishing as the process goes on, followed by nearly isothermal conduction-dominated solidification, and finally, cooling of the solid PCM, once the solidification process is complete. The shortest discharging time is achieved for the lowest HTF inlet temperature, 7 °C.

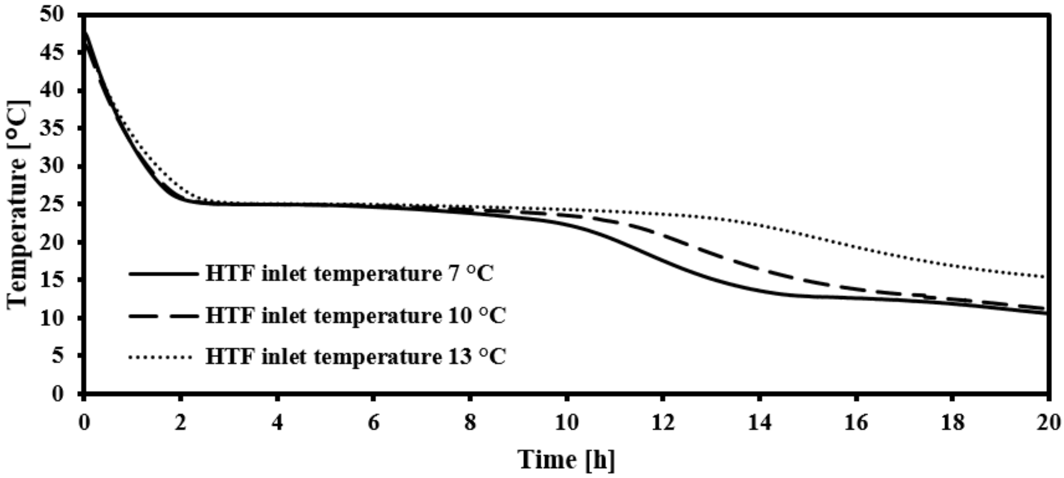


Fig. 7. Experimentally acquired transient PCM temperature variations inside the LTES at position x = 0.2 m, r = 0.035 m (position 1) during discharging processes with different HTF inlet temperatures

Transient PCM temperature variations for various radial positions at axial position 0.75 m (positions 4, 5 and 6) and for HTF inlet temperature 7 °C are presented in Fig. 8. Comparing with Fig. 7 can be observed that lower measurement positions, further from the HTF inlet, have longer solidification times than higher positions.

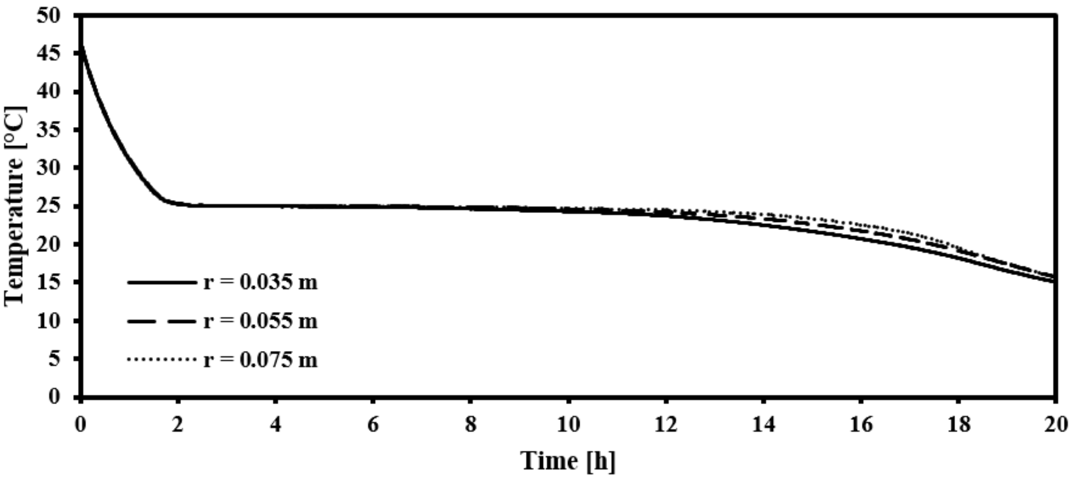


Fig. 8. Transient PCM temperature variations inside the LTES during discharging with HTF inlet temperature 7 °C, at axial position x = 0.75 m and for different radial positions (positions 4, 5 and 6)

Furthermore, comparing with previous figures, it can also be observed that discharging processes are noticeably slower than charging processes, due to lack of natural convection during solidification and increasingly higher thermal resistance provided by solidified PCM.

3.3. Stored thermal energy

In order to obtain LTES heat storing capability, as well as to validate performed measurements, cumulative amounts of thermal energy on HTF and PCM sides, for both charging and discharging processes, have been calculated according to the equation:

$$Q = \sum_i^n \dot{V}_{HTF} \cdot \rho_{HTF} \cdot c_{HTF} \cdot (t_{in,HTF} - t_{out,HTF}) \cdot \Delta\tau = m_{PCM} \cdot L + \sum_i^n m_{PCM} \cdot c_{PCM} \cdot (\bar{t}_{PCM} - \bar{t}_{PCM}^0) \qquad \text{(eq. 1)}$$

Amounts of thermal energy stored in LTES during charging and released during discharging, for different HTF inlet temperatures, are represented in Fig. 9.

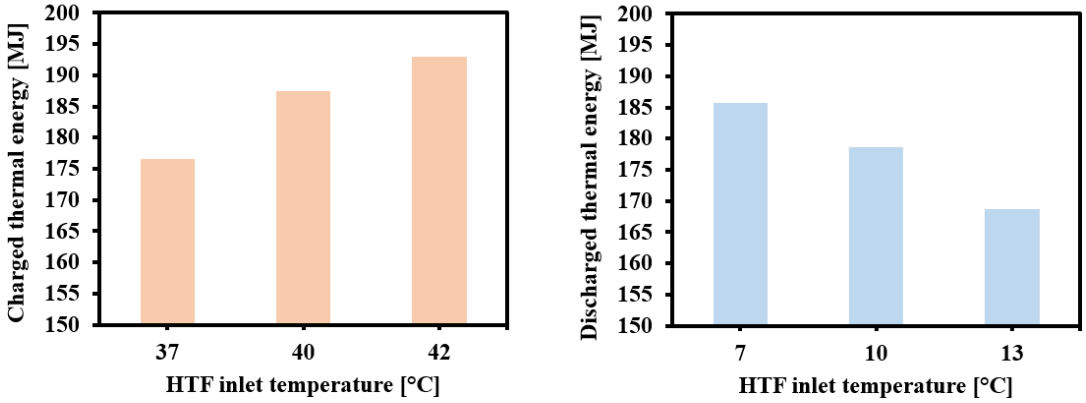


Fig. 9. Comparison of stored thermal energy during charging and released thermal energy during discharging

As seen from Fig. 9, the highest amount of stored thermal energy (193.1 MJ) during charging analyses is achieved for the highest HTF inlet temperature, 42 °C. The highest amount of released thermal energy (185.7 MJ) in discharging analyses is obtained for the lowest HTF inlet temperature, 7 °C.

4. Conclusion

Influence of HTF inlet temperature on charging and discharging processes inside a vertically oriented shell-and-tube type LTES with longitudinal fins has been experimentally analyzed. It can be observed that charging and discharging processes are the shortest for highest and lowest HTF inlet temperatures, respectively. Also, natural convection is the dominant heat transfer mechanism in charging processes, and is negligible in discharging processes, which are conduction-governed. Amounts of stored and released thermal energy for analyzed processes have been calculated. Obtained results can be used in further analyses and numerical modeling of heat transfer in the longitudinally-finned LTES, as well as modeling of thermal systems incorporating this type of LTES tank.

List of symbols

m_{PCM} – PCM mass [kg]

L – PCM latent heat [kJ/kg]

c_{PCM} – PCM specific heat capacity [kJ/kgK]

$\bar{t}_{PCM}$ – PCM average temperature in current measurement timestep [°C]

$\bar{t}_{PCM}^0$ – PCM average temperature in previous measurement timestep [°C]

$\dot{V}_{HTF}$ – HTF volume flow rate [m^3/s]

ρ_{HTF} – HTF density [kg/m^3]

c_{HTF} – HTF specific heat capacity [kJ/kgK]

$t_{in,HTF}$ – HTF inlet temperature in current measurement timestep [°C]

$t_{out,HTF}$ – HTF outlet temperature in current measurement timestep [°C]

$\Delta\tau$ – measurement interval (timestep) [s]

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