SUSHEAT

Smart Integration of Waste and Renewable Energy for Sustainable Heat Upgrade in the Industry

D4.5 Lab-scale TES design

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Executive Summary

This deliverable includes one of the key achievements of WP4 “Thermal Energy Storage: Design and Optimization” which concerns the development and testing of the revolutionary TES design of a bio-inspired thermal energy storage (TES) tank developed in the project SUSHEAT. To improve the thermal performance of the latent heat thermal energy storage system and the SUSHEAT technology, the principles of biomimetics were applied to develop a TES tank that mimics the structure of a biological system. Moreover, additive manufacturing technology was used to overcome constraints during manufacturing. The design started at the beginning of the project, and the first experiment were obtained by October 2023. The proof of concept of the TES was published in “*Cabeza, L. F., Mani Kala, S., Zsembinszki, G., Vérez, D., Risco Amigó, S., Borri, E. (2024). Development of a bio-inspired TES tank for heat transfer enhancement in latent heat thermal energy storage systems. Applied Sciences (2024) 14 2940*”. In parallel to the experiments, CFD simulations were carried out to understand the behaviour of the new developed tank and to provide inputs for the design optimization for the final design that will be developed with the generic algorithm. The outcomes of the CFD simulations provided useful information regarding PCM temperature and HTF velocity distribution inside the TES tank. As a result, some modifications were proposed in the distribution of the pipes as well as in the basic geometrical configuration of the TES tank, building a second optimized prototype. This deliverable shows the design, the experimental tests, and simulations of the prototypes of the bio-inspired TES tanks developed, manufactured, and tested in SUSHEAT. The final optimized design with artificial intelligence of the bio-inspired tank will be 3D printed and tested at lab scale in a later stage of the project, and the results will be in the final report of the SUSHEAT project.

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Glossary of terms and abbreviations

Acronyms

CAD	computer aided design
CFD	computational fluid dynamics
DSC	differential scanning calorimetry
GA	Grant Agreement
HTF	heat transfer fluid
PCM	phase change material
TES	thermal energy storage

Symbols

m	mass
T	Temperature
t	time
c_p	specific heat capacity

Greek letters

Subscripts

In	Inlet
Out	Outlet

1. Introduction

This deliverable includes one of the key achievements of WP4 “Thermal Energy Storage: Design and Optimization” which concern the development and the testing of the revolutionary TES design of a bio-inspired thermal energy storage (TES) tank developed in the project SUSHEAT.

To improve the thermal performance of the latent heat thermal energy storage system and the SUSHEAT technology, the principles of biomimetics were applied to develop a TES tank that mimics the structure of a biological system. By mimicking the fluid flow path of a biological system through a branching tree-like structure, the heat transfer fluid flow path was engineered to increase the effective heat transfer surface area [1]. The TES tank, which has a branched flow network for the heat transfer fluid, was constructed using additive manufacturing technology. Moreover, additive manufacturing technology has the advantage of a longer thermal conductive path for heat transfer and may construct complicated parts and bifurcation points on fluid flow passages without discrete joints. The authors believe that the bio-inspired TES tank design based on additive manufacturing technology effectively addresses the lower discharging rates of latent heat thermal energy storage systems.

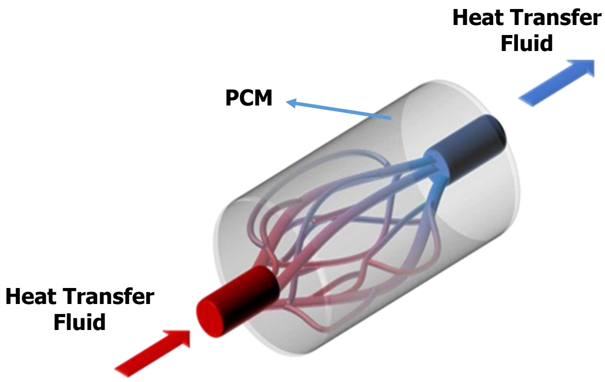


Fig. 1. Bio-inspired TES tank concept [1].

The design started at the beginning of the project, and the first experimental results were obtained by October 2023. The proof of concept of the TES was published in “*Cabeza, L. F., Mani Kala, S., Zsembinszki, G., Vérez, D., Risco Amigó, S., Borri, E. (2024). Development of a bio-inspired TES tank for heat transfer enhancement in latent heat thermal energy storage systems. Applied Sciences (2024) 14 2940*”.

Some delays in the experimentation occurred due to a leakage detected in the tank during the testing with salt hydrates. In this case, the tank had to be shipped back to the manufacturer for reparation. In parallel to the experiments, CFD simulations were carried out to understand the behaviour of the newly developed tank and to provide inputs for the design optimization for the final design that will be developed with the generic algorithm.

The final optimized design of the bio-inspired tank will be 3D printed and tested at lab scale in a later stage of the project, and the results will be in the final report of the SUSHEAT project.

1.1. Mapping SUSHEAT outputs

Table 1. Adherence to SUSHEAT GA [2] deliverable & tasks descriptions.

TASKS	
Task T4.5 - Lab-scale experimental evaluation of the newly designed TES tank	**Section 2 to Section 5,**
This task will take advantage of novel additive manufacturing technologies to test the designs obtained in T4.4. For this purpose, a fused deposition metal 3D printer will be employed. The tanks tested will have a maximum capacity of 2 kWh. Parametric analysis of the designs obtained in T4.4 will be performed. At least three iterative cycles of design - manufacture - experimental parameterization will be performed These iterative designs will use both AI techniques and CFD to validate the previous results previously obtained T4.3 and T4.4.	This deliverable reports in Section 2 the innovative concept of bio-inspired TES design, which was 3D printed and tested, with results shown in Section 3. The CFD simulations were used to understand the physical behaviour of the tank and support future optimization, and are shown in Section 4. The optimized AI tank shown in D4.4 will be 3D printed and tested throughout the project, and the results will be included in the next technical report.
DELIVERABLE	
D4.5 - Lab-scale TES design	**Section 2 to Section 5**
Final results of the parametric analysis of TES. The CFD and IA models will be described, and the design after each of the three iterations of the complete process will be presented (T4.5).	The TES tank with the bio-inspired design is shown in Section 2. The experimental results compared with a conventional TES are shown in Section 3. CFD models and results are shown in Section 4.

1.2. Deliverable overview and structure

The first and second prototype of the bio-inspired tank developed and manufactured is shown in Section 2. Section 3 shows the methodology and results of the experimental testing of both prototypes of lab-scale bio-inspired TES. CFD modelling and results are instead shown in Section 4. Section 5 summarizes the conclusions of this report.

2. TES tank design

2.1. First prototype of bio-inspired TES tank

In order to prove the concept of a bio-inspired TES, a first prototype was developed, built and tested. In this case, the design was based on the idea of developing a heat exchanger with a branching design inspired by a capillary system of the human body and plants, breaking the concept of a conventional tube heat exchanger. For proof of concept, no optimization tools were implemented. The main idea was to have a first test of experimental data to test and prove the bio-inspired TES concept and provide first inputs for both simulations and the generic algorithm to optimize the design.

The first prototype of the bio-inspired TES designed using computer-aided design (CAD) is shown Fig. 2. The tank has a capacity of 3 liters of PCM with a storage capacity of 0.15 kWh. The heat exchanger of the TES tank mimics the structure of a biological fluid flow network, and it is contained inside a shell structure made of aluminium.

From the Figure 2, it is possible to notice that the heat transfer fluid (HTF) inlet tube of the TES tank narrows until it reaches the first bifurcation point, at which it separates into branches. In particular, the TES tank HTF tubes branch into seven new tubes in a symmetrical pattern. Table 2 summarizes the design of the bio-inspired TES tank and the geometric dimensions. Due to the complex biomimetic design of the tank, additive manufacturing based on 3D printing was chosen as a methodology to produce the novel TES.

Table 2. Geometric dimensions of the bio-inspired TES tank.

Description	**Dimensions**
Outer diameter of the HTF tube at the inlet and outlet	11 mm
Thickness of the HTF tube at the inlet and outlet	0.648 mm
Diameter of the HTF at the bifurcation point of level 0	8 mm
Diameter of the HTF at the bifurcation point of level 1	6 mm
Angle between the level 0 branches and the axis of the TES tank	59°
Angle between the level 1 branch and the axis of the TES tank	59°
Total number of HTF tubes at level 2	49
Volume of the bio-inspired TES tank (shell side)	3 L
Heat transfer surface area	66,248 mm^2

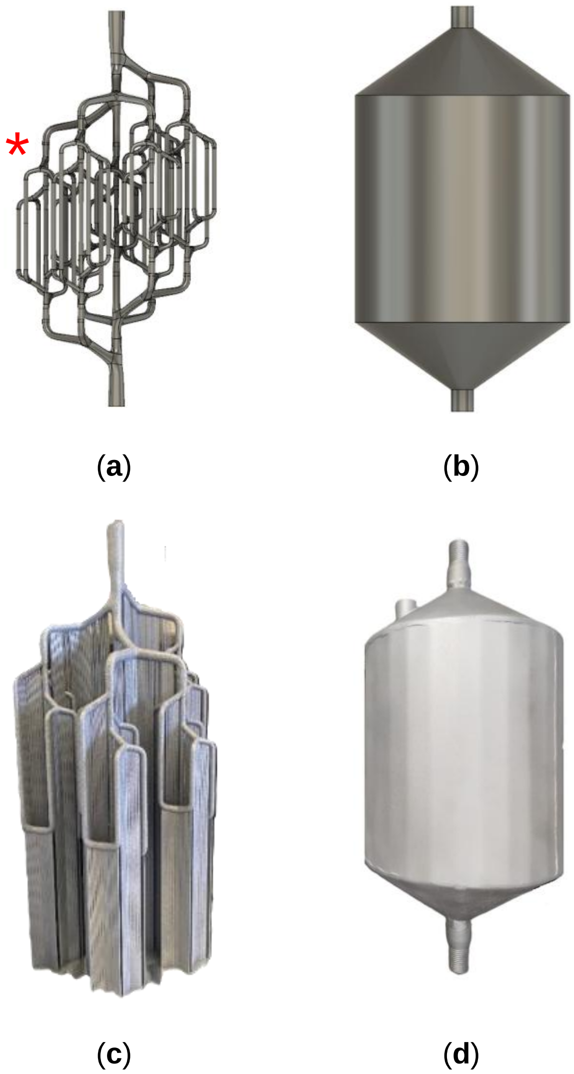


Fig. 2. Schematic representation and pictures of the TES tank: (a) CAD design of the bio-inspired HTF tubes of the TES tank, (b) CAD design of the shell of the TES tank, (c) picture of the bio-inspired HTF tubes during the additive manufacturing process, and (d) picture of the final bio-inspired TES tank ("*" represents the position of the thermocouple) [1].

2.2. Second prototype of bio-inspired TES tank

After a comprehensive experimental testing carried out in the laboratory of the UDL with the first prototype of bio-inspired TES tank, the next step was to identify the main drawbacks and limitations of the first prototype for further improvement and final optimization of the TES tank design. The CFD simulations performed by ADSC with the first prototype provided useful information regarding PCM temperature and HTF velocity distribution inside the TES tank.

As a result, some modifications were proposed in the distribution of the pipes as well as in the basic geometrical configuration of the TES tank. First, the orientation of the TES tank was changed from vertical to horizontal, with the HTF inlet pipe at the bottom and outlet at the top. Second, the central pipe that in the first prototype connected directly the inlet and the outlet was removed to avoid a preferential HTF flow in the central part and allow for a better HTF distribution inside the TES tank. Finally, additional pipes were added close to the HTF inlet and outlet to connect the main branches and fill the gaps identified in these parts of the first prototype.

Therefore, a second prototype of the bio-inspired TES designed using CAD was created, as shown in Fig. 3. The tank had the same capacity of 3 litres of PCM as the first prototype, to make the comparison of the behaviour of the two prototypes easier. The new heat exchanger was then 3D printed in the same material and placed inside a shell structure made of aluminium. In this case, three temperature sensors were placed inside the tank to measure the PCM temperature at different locations.

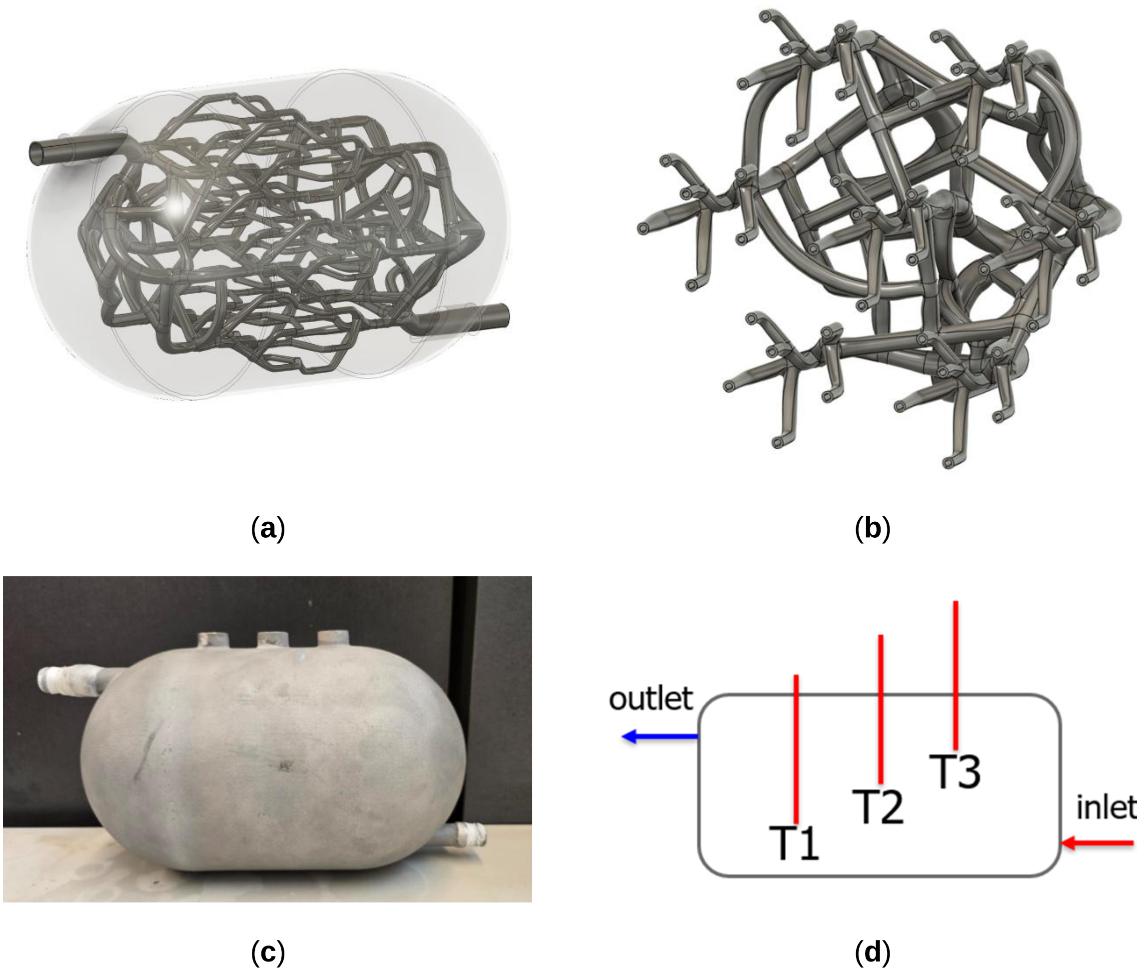


Fig. 3. Schematic representation and pictures of the second prototype: (a) CAD design of the HTF pipes of the full TES tank, (b) CAD design of the additional HTF pipes connections close to the inlet/outlet of the TES tank, (c) picture of the final TES tank after 3D printing and placement inside the shell, and (d) schematic of location of the temperature sensors inside the TES tank.

In this case, the TES tank HTF tubes branch into only six new tubes, since the central tube was removed. Moreover, the first branching of the pipes connecting with the main pipe was not symmetric because the main pipe was not placed at the central axis of the TES tank; therefore, branches at level 1 were distributed in different orientations to fill the volume of the tank. Fig. 3 summarizes the design of the second bio-inspired TES tank, the geometric dimensions.

Table 3. Geometric dimensions of the second bio-inspired TES tank.

Description	**Dimensions**
Outer diameter of the HTF tube at the inlet and outlet	11.7 mm
Thickness of the HTF tube at the inlet and outlet	0.648 mm
Diameter of the HTF at the bifurcation point of level 0	9.5 mm
Diameter of the HTF at the bifurcation point of level 1	5.5 mm
Angle between the level 0 branches and the axis of the TES tank	Variable
Angle between the level 1 branch and the axis of the TES tank	46°
Total number of HTF tubes at level 2	42
Volume of the bio-inspired TES tank (shell side)	3 L
Heat transfer surface area	≈83,500 mm^2

3. Lab-scale test of the bio-inspired tank

3.1. Methodology

3.1.1. Experimental evaluation

The charging and discharging characteristics of the bio-inspired TES tank developed for the project SUSHEAT were evaluated using a custom-built experimental setup, shown in Figure 4.

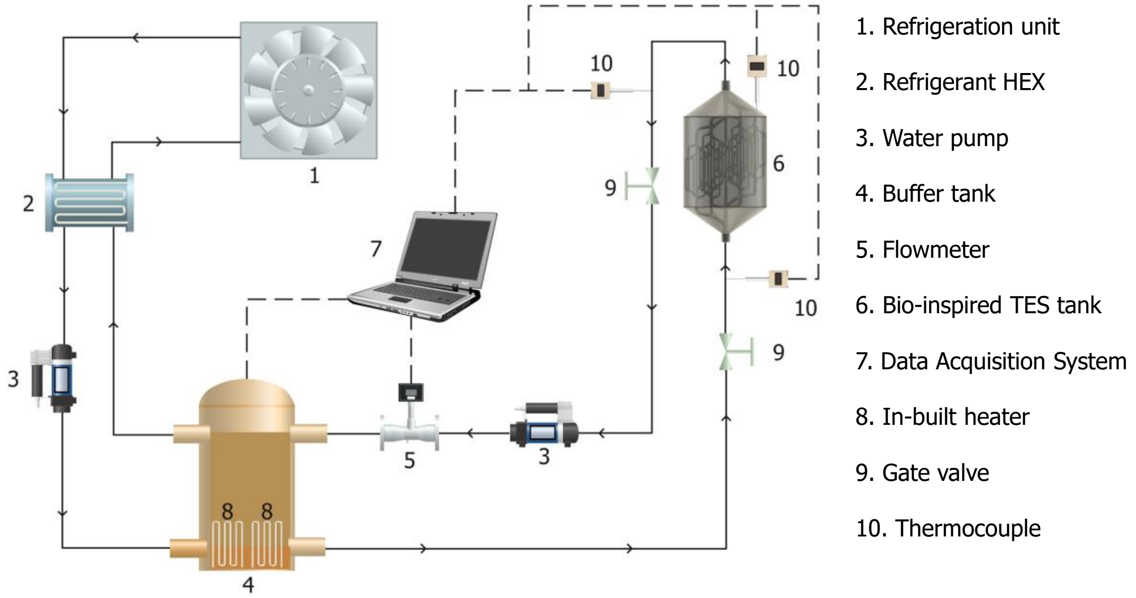


Fig. 4. Schematic of the experimental set-up at UDL [1].

In this setup, water used as heat transfer fluid for the experiments is cooled down or heated up in a buffer tank of 200 L capacity using a refrigeration unit (Zanotti uniblock, GCU2020ED01B) or a 3-kW electric resistance. Then pumped through pipes and flowed through the TES tank at a constant flow rate using a volumetric pump (Pentax, PM45 0.5 HP, Veronella (Italy)). A flowmeter (Badger Meter ModMAG, M1000, Barcelona (Spain)) measures the flow rate of the HTF with an uncertainty of 0.3%. One thermocouple (TMQSS-IM050U T-type) placed in the TES tank measured the PCM temperature with an accuracy of ±0.3 °C and two thermocouples (Pt-100 1/5 DIN class B) placed at the inlet and outlet of the TES tank measured the HTF temperature. The temperature–time data were recorded using a data acquisition system (STEP, DL01-CPU, Barcelona, Spain). The heat loss to the surroundings was reduced using polyurethane foam for copper pipes and polystyrene for the TES tank.

For the testing, two different PCM were selected:

- Organic PCM: Pure n-octadecane (90%)
- Inorganic PCM

The selection of PCMs was limited by the condition of the experimental setup, which uses water as a heat transfer fluid (HTF). Pure n-octadecane (90%) with a melting point of 28 °C, purchased from Alfa Aesar, Karlsruhe (Germany) was chosen due to its well-known noble properties and excellent behavior during the phase change. In the case of inorganic PCM, a selection was made combining literature review and experimental tests. From the literature PCMs available with melting points around 28 °C were

- $CaCl2 \cdot 6H_2O$
- $Mn(NO_3)_2 \cdot 6H_2O$
- $LiNO_3 \cdot 3H_2O$
- $Na_2CO_3 \cdot 10H_2O$

$LiNO_3 \cdot 3H_2O$ was disregarded due to its unavailability. For the other three PCMs, differential scanning calorimetry (DSC) and ice pond test were done to evaluate the latent heat and the subcooling, respectively. In this last case, PCMs in liquid state were put in a test-tube immersed in a bath at 10 ºC to solidify. 5 shows the results of the ice pond test, where it is possible to notice that Mn(NO3)2·6H2O is the one that showed the minimum subcooling effect, being the PCM finally selected for the experiments.

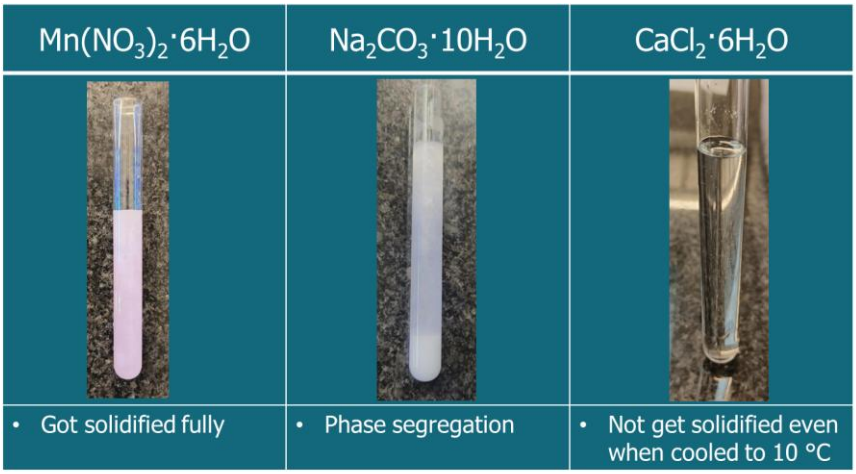


Fig. 5. Subcooling tests of inorganic PCMs

As a first step of the experimental testing, the PCM was filled into the bio-inspired TES tank. Then, after the tank was mounted in the setup, the TES was charged (heated) or discharged (cooled).

During the experiment, the impact of varying the HTF operating temperature and flow rate on the thermal performance of the bio-inspired TES tank was investigated.

Initially, the HTF flow rates were set at three different values: 1.5, 3 and 6 L/min, and at two distinct operating temperature ranges, between 15 ± 1 °C and 45 ± 1 °C and between 20 ± 1 °C and 35 ± 1 °C. Based on the initial results obtained, the parameters were subsequently narrowed to 1.5 and 3 L/min, with the operating temperature window adjusted to 15 ± 1 °C to 45 ± 1 °C.

To prove the concept, the bio-inspired TES developed in SUSHEAT was compared with a conventional shell-and-tube TES shown in 6. Table 4 summarizes the characteristics of the conventional shell-and-tube TES tank with respect to the geometric dimensions. As per the bio-inspired TES, the shell-and-tube TES tank can hold 3 liters of liquid PCM having the same volumetric capacity.

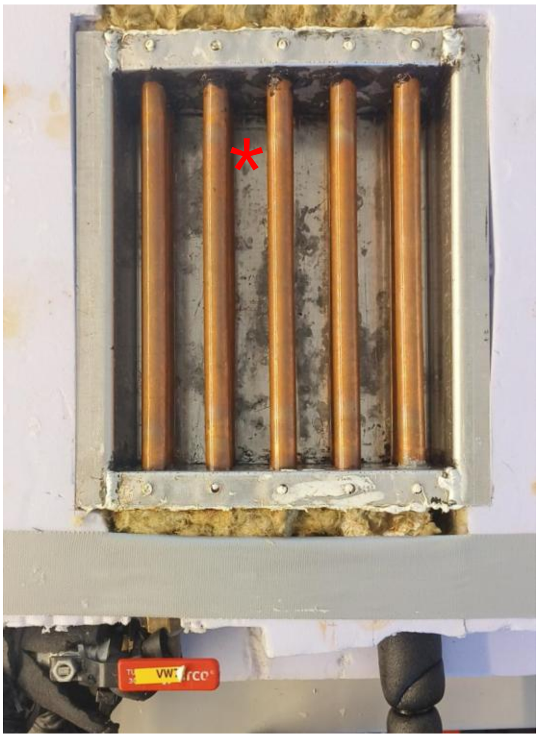


Fig. 6. Picture of the shell-and-tube TES tank ("*" represents the position of the thermocouple) [1].

Table 4. Geometric dimensions of the conventional shell-and-tube TES tank.

Description	**Dimensions/Quantity**
Number of tubes	10
Length of the tubes	247 mm
Diameter of the tubes	16.2 mm
Heat transfer surface area	12,983 mm^2
Volume of shell-and-tube TES tank	3 L

In order to compare both TES, thermocouples were strategically positioned in both the conventional shell-and-tube TES tank and the bio-inspired TES tank to measure the temperature of the PCM. The temperature sensor in a conventional shell-and-tube TES tank is positioned precisely in the middle of the gap between the HTF tubes at the rear part of the tank. In the bio-inspired TES tank, on the other hand, the temperature sensor was positioned between the tank wall and the outermost branch of the HTF tubes. This thermocouple placement guarantees that by the end of the charging/discharging, all the PCM in the TES tank will be in a fully liquid or solid state. The position of the thermocouples in the TES tanks is represented with the symbol "*" in Figures 2 and 6.

3.1.2. Performance indicators

To determine the performance of the bio-inspired TES tank, three main indicators were considered:

- charging time
- discharging time
- energy charged/discharged
- thermal power

The charging time was defined as the time to take the PCM temperature from the initial temperature (15 °C or 20 °C) to the final (29 °C).

Similarly, the discharging time was defined as the time to take the PCM to complete the solidification from 45 °C or 35 °C to 23.5 °C.

The energy charged/discharged was determined using the following formula:

$$\boldsymbol{Energy} = \sum_{T_{PCM,i}}^{T_{PCM,f}} \dot{m} C_p |T_{HTF,in} - T_{HTF,out}| \Delta t \qquad (1)$$

where $\dot{m}$ is the mass flow rate of the HTF, C_p is the specific heat capacity of the water, $T_{HTF,in}$ and $T_{HTF,out}$ are the temperatures of the HTF at the inlet and outlet of the TES tank, respectively, T_{PCM} is the temperature of the PCM, and Δt is the time interval between two readings. The $T_{PCM,i}$ and $T_{PCM,f}$ correspond to initial and final PCM temperatures, respectively.

The mean power was determined using the following formula:

$$\boldsymbol{Mean\ Power} = \frac{\sum_{T_{PCM,i}}^{T_{PCM,f}} \dot{m} C_p |T_{HTF,in} - T_{HTF,out}| \Delta t}{t} \qquad (2)$$

Where t is the time taken for the PCM to vary from the minimum temperature to the maximum temperature.

3.2. Results

3.2.1. First bio-inspired TES with organic PCM

This section shows the results of the first prototype of bio-inspired TES with organic PCM. These experiments were published in [1]. Figures 7 and 8 show the comparison between the phase transition behaviour of the PCM in the first design bio-inspired TES tank and the conventional shell-and-tube TES tank during the charging and discharging cycles, respectively. In this case, the comparison was carried out with the HTF flow constant at 3 L/min.

From Figure 7, it is shown that both the shell-and-tube and the bio-inspired TES tank took a similar amount of time (0.45 h and 0.49 h) for charging. Moreover, the temperatures vs. time in both cases were similar during the cycle. The figure also shows the power of charging, which in this case, is slightly lower for the bio-inspired TES, which could be affected by the different convection movements that are created in both tanks. The performance during the discharging of both tanks is shown in Figure 8.

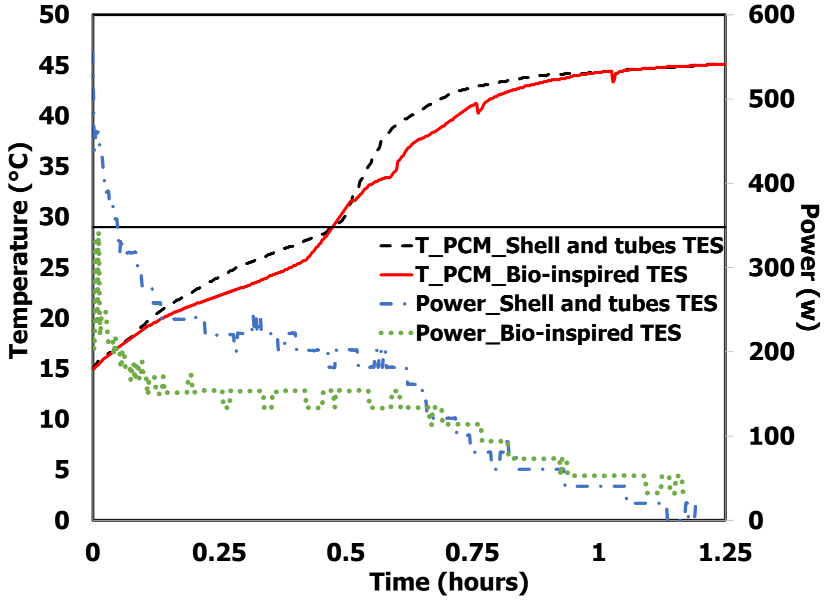


Fig. 7. Comparison between shell-and-tube and bio-inspired TES tanks during the charging cycle [1].

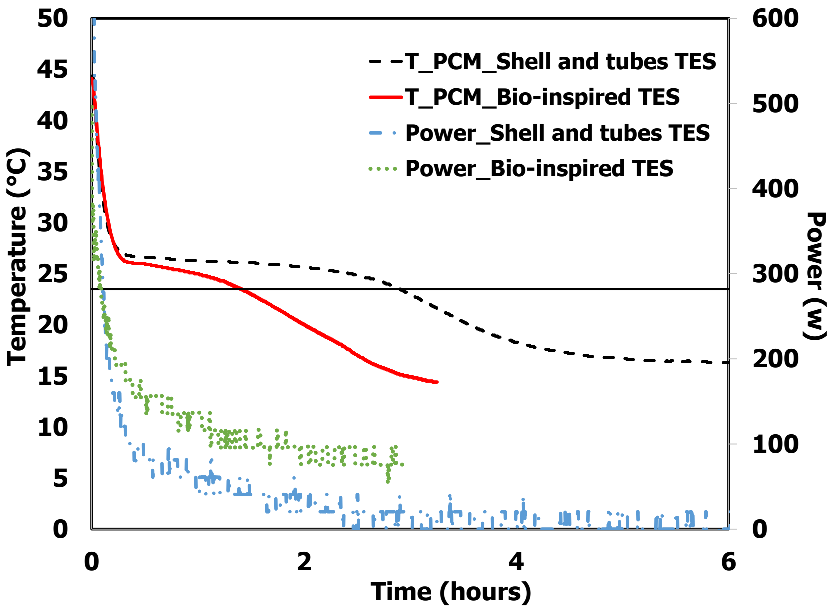


Fig. 8. Comparison between shell-and-tube and bio-inspired TES tanks during the discharging cycle [1].

During the beginning of the discharging cycle, the temperature profile was similar among the shell-and-tube and bio-inspired TES tanks. In this case, results showed that the discharging rate was substantially higher for the bio-inspired TES tank. Figure 8 also shows that the time required for the TES tank to discharge the heat stored in the PCM was 1.4 h for the bio-inspired TES tank, 52% less than the shell-and-tube TES tank (2.8 h). Indeed, in discharging, the influence of convection is reduced, and the highest heat transfer area of the bio-inspired tank enhances the power of discharging.

The charging and discharging behaviour of the bio-inspired TES was also evaluated by varying the HTF mass flow rate, and which results are shown in Figure 9. In all cases, regardless of the HTF mass flow rate, the temperature difference between the HTF inlet and outlet remained constant during the phase change process. Nevertheless, it is possible to notice that the temperature difference is higher for a lower mass flow rate which has a better heat exchange with the heat transfer fluid.

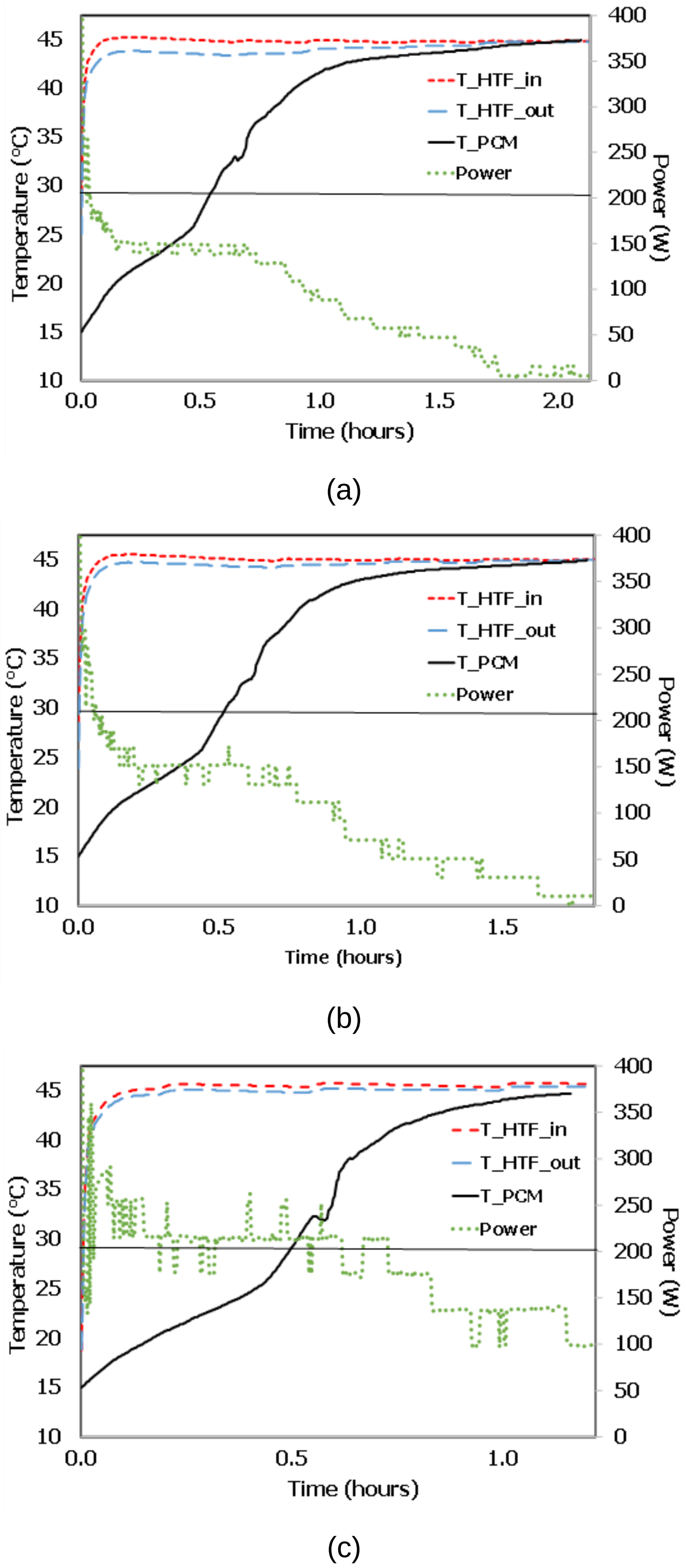
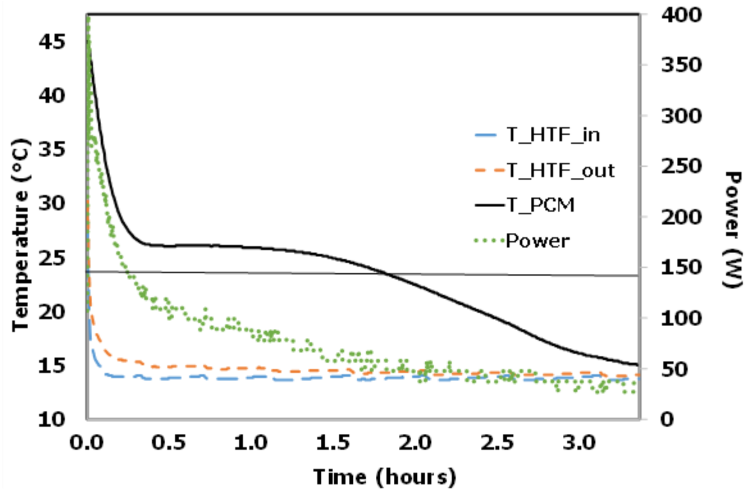
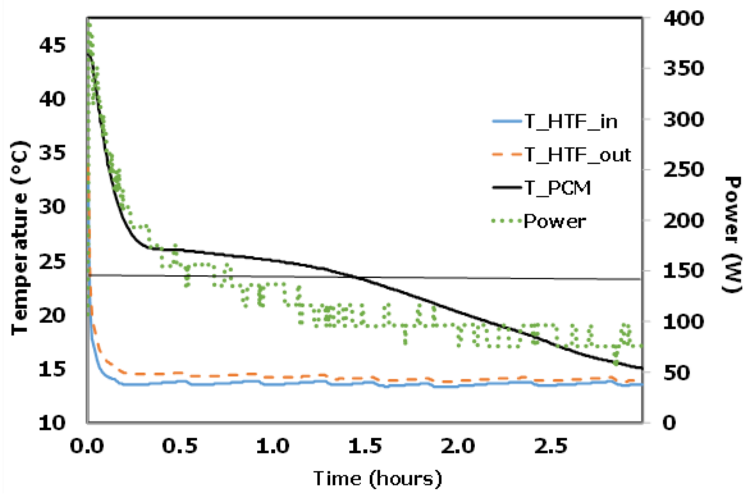


Fig. 9. Variations in power, PCM temperature, and HTF inlet and outlet temperatures with respect to time at three distinct HTF flow rates: (**a**) 1.5 L/min, (**b**) 3 L/min, and (**c**) 6 L/min during the charging cycle [1].

The discharging characteristics of the bio-inspired TES tank under three distinct mass flow rates are shown in Figure 10.



(a)



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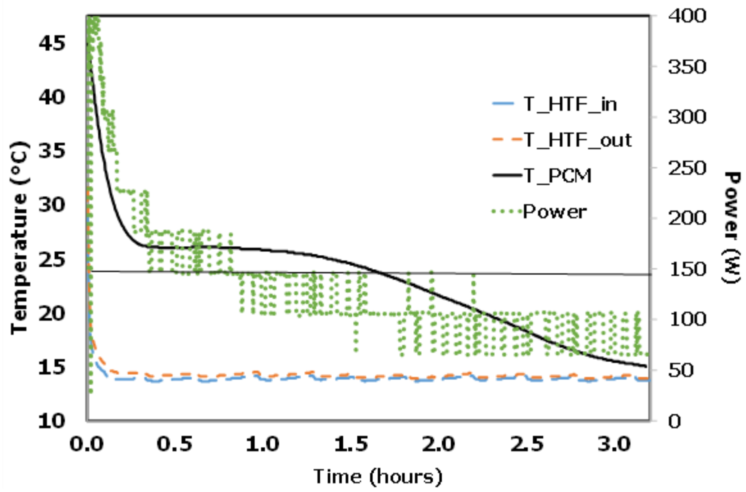


(c)

Fig. 10. Variations in power, PCM temperature, and HTF inlet and outlet temperatures with respect to time at three distinct HTF flow rates, (a) 1.5 L/min, (b) 3 L/min, and (c) 6 L/min during the discharging cycle [1].

During the initial stages of the discharging cycle, there was a substantial temperature differential between the HTF inlet and HTF outlet since the PCM was at a high temperature (45 °C) and the heat exchanged was higher than during the final stages of the discharging. However, regardless of the HTF mass flow rate, the temperature difference between the HTF inlet and outlet remained nearly constant during the phase change process.

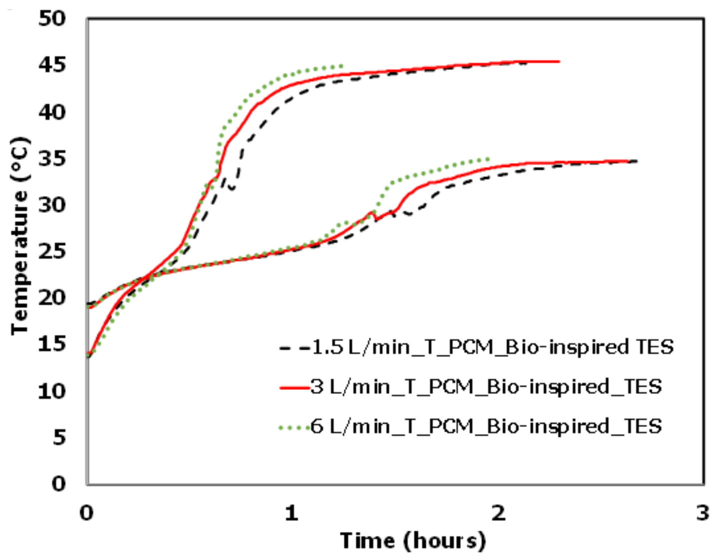
Also, in this case, the temperature difference between the inlet and outlet is higher in a lower mass flow rate, showing a higher efficiency of heat transfer between the HTF and the PCM. The power transferred by the TES tank during the discharging cycle is similar to that in the charging cycle. Setting a HTF mass flow rate of 6 L/min, the TES delivers the highest power output throughout the phase transition process. The bio-inspired TES tank with a 3 L/min HTF flow rate took the least time (1.4 h) to discharge the PCM. However, those with flow rates of 1.5 L/min and 6 L/min required 1.6 h to reach 23.5 °C.

The effect of the HTF inlet temperature on the charging and discharging behaviour of the bio-inspired TES tank was studied at three different mass flow rates of the HTF. Accordingly, the operating temperature range was reduced from 15–45 °C to 20–35 °C for comparison (Fig. 11).

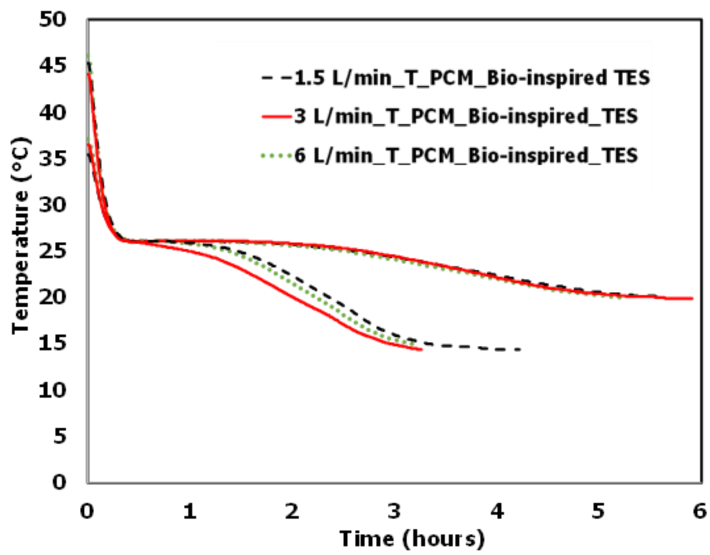
The bio-inspired TES tank was charged with two different HTF inlet temperatures, 45 °C and 35 °C, and discharged with two different HTF inlet temperatures, 15 °C and 20 °C. Figure 11 shows that for the TES system supplied by the highest/lowest HTF inlet temperature, there was a significant increase in the rate of PCM melting during the charging cycle and solidification during the discharging cycle, respectively. In those cases, the PCM temperature changed rapidly during the charging and discharging cycles because of the larger temperature difference between the HTF and PCM temperatures. The PCM melted and solidified more quickly during the charging and discharging processes, respectively, because of the increased heat transfer rate brought about by the highest/lowest inlet temperature.

Figure 12 shows a comparison of the mean power for different HTF flow rates and HTF operating temperatures for both charging and discharging cycles. The mean power was obtained using Eq. (2), where the initial PCM temperature ($T_{PCM,i}$) was 15 ºC or 20 ºC for the charging cycle and 35 º or 45 ºC for the discharging cycle, while the final PCM temperature ($T_{PCM,f}$) corresponded to 29 ºC for the charging cycle and 23.5 ºC for the discarging cycle. It is evident that the mean power transferred by the TES tank is more significantly impacted by the inlet temperature of the HTF.

Figure 11 also indicates that with an increase in HTF flow rate, the mean power produced by the bio-inspired TES tank increased in both operating temperature ranges. It was additionally found that the bio-inspired TES tank with the HTF flowing at 6 L/min had the highest mean power transferred in both operational temperature ranges during the charging and discharging cycles. The highest mean power transferred by the bio-inspired TES is, however, proportional to the temperature at which the HTF transports its thermal energy. During the charging and discharging cycles, HTF flowing at 6 L/min with the wider operating range had 133.6% and 101.5% higher mean power transferred, respectively, compared to the lower operating temperature range.

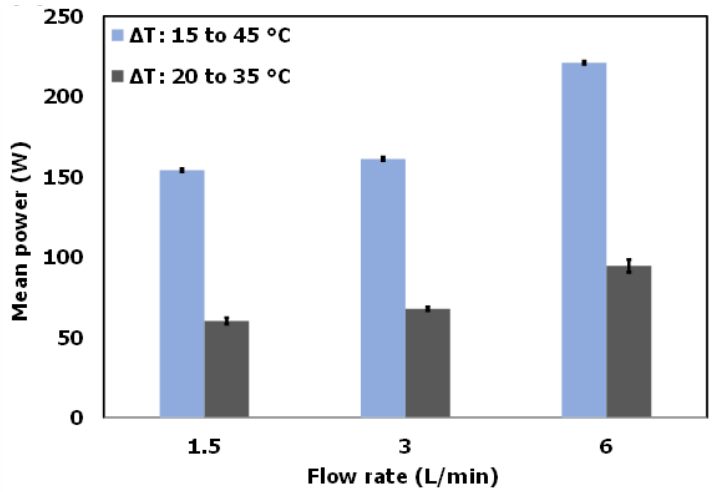


(a)

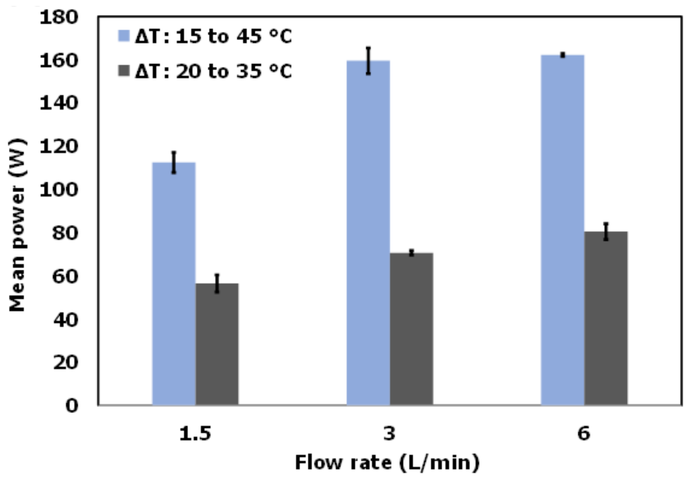


(b)

Fig. 11. Effect of HTF inlet temperature on the temperature vs. time profile of the PCM during (a) the charging cycle and (b) the discharging cycle [1].



(a)



(b)

Fig. 12. Comparison of mean power vs. flow rate for the bio-inspired TES during (a) the charging cycle and (b) the discharging cycle [1].

Therefore, the change in HTF inlet temperature has a strong influence on the charging and discharging time of the PCM. When the HTF temperature was raised from 35 °C to 45 °C, the PCM melting time was significantly shortened from 1.29 h to 0.47 h.

The Ragone plot (Figure 13) makes it clearly apparent that the bio-inspired TES tank performed better than the conventional shell-and-tube TES tank design. In particular, the bio-inspired TES tank operated optimally in the operational temperature range of 15 °C to 45 °C and at an HTF flow rate of 6 L/min.

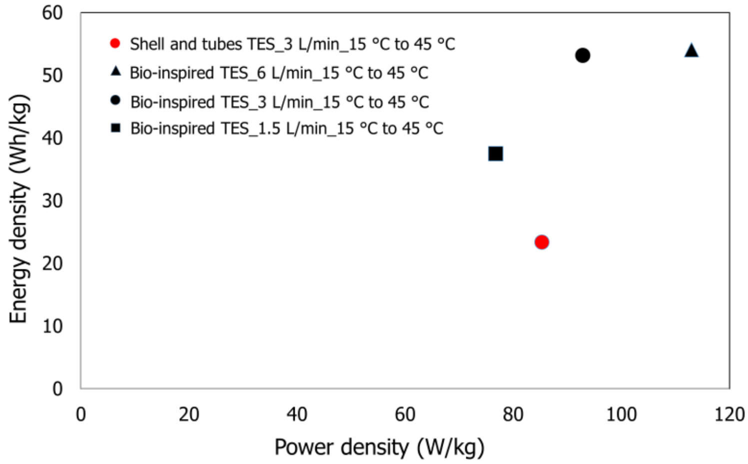


Fig. 13. Performance comparison between a conventional shell-and-tube TES tank and the bio-inspired TES tank [1].

3.2.2. First bio-inspired TES with inorganic PCM

Results of this section are reported in the document "Confidential results for D4.5 Labe-scale TES design".

3.2.3. Second design bio-inspired TES with inorganic PCM

Results of this section are reported in the document "Confidential results for D4.5 Labe-scale TES design".

4. CFD simulations of the bio-inspired tank

4.1. Methodology

The loading and the unloading stages have been simulated with CFD tools (Ansys 2024 Fluent) to analyze the behavior of the process. To fulfil this task, the volumes where the selected PCM and HTF occupy have been subdivided into smaller volumes (cells), forming a computational mesh. In each of these cells, the Navier-Stokes governing equations are applied iteratively to obtain the detailed results in the whole TES volume.

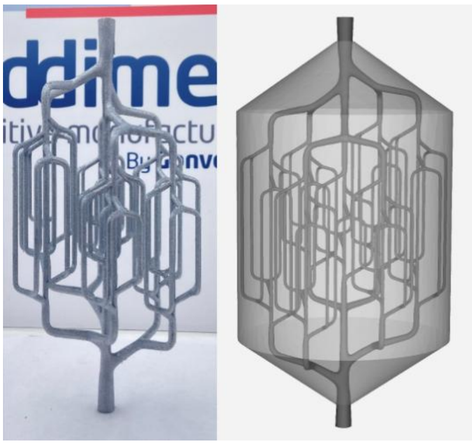


Fig. 14. Pipes of the real-life TES tank (left), TES tank used for the CFD simulations (right) [1]

Fig. 14 shows the TES tank that has been used for the CFD simulations. Its design has been developed by UdL, and the CFD simulations have been made by ADSC. In order to study the performance of the tank shown above, the obtained mesh contained 30370746 cells.

The analyzed PCM is n-octadecane, whose melting point is 27.7 ºC. The selected heat transfer fluid for this process is water and will enter the system at a temperature higher than the PCM melting point.

In order to define the cases used to study both loading and unloading of the TES tank, the working conditions will be named below:

Loading of the TES tank

- Simulation time: 30 min
- HTF volume flow: 3 L/min
- HTF inlet temperature: 45 ºC
- PCM initial temperature: 15 ºC

Unloading of the TES tank

- Simulation time: 30 min
- HTF volume flow: 3 L/min
- HTF inlet temperature: 15 ºC
- PCM initial temperature: 42.5 ºC

4.2. CFD Results

Results of this section are reported in the document “Confidential results for D4.5 Labe-scale TES design”.

5. Conclusions

This deliverable includes one of the key achievements of WP4 “Thermal Energy Storage: Design and Optimization” which concerns the development and testing of the revolutionary TES design of a bio-inspired TES tank developed in the project SUSHEAT. To improve the thermal performance of the latent heat thermal energy storage system and the SUSHEAT technology, the principles of biomimetics were applied to develop a TES tank that mimics the structure of a biological system. Moreover, additive manufacturing technology was used to overcome constraints during manufacturing. The design of the first prototype started at the beginning of the project, and the first experimental results were obtained by October 2023. Results showed that without any optimization the tank performed better than a conventional showing its potential.

The CFD simulations show similar results to the experiments, as it is proved by comparing both temperature curves. The CFD simulations demonstrate how faster the unloading stage is compared to the loading stage, during the first 30 minutes of operation, as the temperature difference is 1.5 times faster in the unloading stage. The same happens with the solidification/melting, as it is 3.6 times faster in the unloading stage than in the loading stage. Even though the unloading stage provides faster results in the current simulation time, after 20 minutes of operation, the loading stage tends to increase faster in both temperature change rate and melting rate. Meanwhile, in the unloading stage, after 20 minutes of operation, the temperature change and the solidification rate will be slower.

The outcomes of the CFD simulations provided useful information regarding PCM temperature and HTF velocity distribution inside the TES tank. As a result, some modifications were proposed in the distribution of the pipes as well as in the basic geometrical configuration of the TES tank, building a second optimized prototype. The second bio-inspired TES prototype was manufactured and tested in June 2025. Results showed an improvement in the performance during charging and discharging compared to the first design. As future work, further optimization will be performed based on the optimized design with the Genetic Algorithm.

References

[1] L.F. Cabeza, S. Mani Kala, G. Zsembinszki, D. Vérez, S. Risco Amigó, E. Borri, Development of a Bio-Inspired TES Tank for Heat Transfer Enhancement in Latent Heat Thermal Energy Storage Systems, Applied Sciences 14 (2024) 2940. https://doi.org/10.3390/app14072940.

[2] European Commission. Grant Agreement Nº 101103552 – SUSHEAT "Smart Integration of Waste and Renewable Energy for Sustainable Heat Upgrade in the Industry". European Climate, Infrastructure and Environment Executive Agency, Horizon Europe.