# Portable PCM-Based Heat Exchanging Thermal Energy Storage System: Performance Testing Using Numerical Model

Benoît Boulay<sup>1</sup>, Syeda Tasnim<sup>2</sup>, Shohel Mahmud

<sup>1</sup>University of Guelph, School of Engineering/Savron Guelph, Canada bboulay@savronsolutions.com; stasnim@uoguelph.ca <sup>2</sup>University of Guelph, School of Engineering Guelph, Canada smahmud@uoguelph.ca

**Abstract** – The performance of three portable PCM-based heat-exchanging TES systems are analyzed using numerical modelling and statistical analysis. The three configurations have the same overall shell dimension, PCM, and heat exchanging fin volumes for a direct performance comparison of the configurations based on geometry alone. Three PCMs (n-heptadecane, calcium chloride hexahydrate and RT21 HC) are considered in the numerical model for each configuration. The numerical model is compared to previous work to ensure validity of the governing equations. The study analyzes a melting and freezing case for each combination for a total of 18 simulations. The key performance indicators are the time to melting/freezing from initial state, time for the average surface Nusselt number to be equal to 1, and the time for the average PCM temperature to reach the process temperature  $\pm 1$  K. The design was tailored to low-grade heat recovery applications such as exhaust process streams and ventilation systems while still being portable and easily handled by one or two people. The results indicate that the proposed heat fin configurations do not significantly affect the performance of the TES system relative to the PCM; however, qualitative analysis suggest that future work could be performed to improve the design into an effective portable heat exchanging energy storage system.

Keywords: Phase change material, latent heat, energy storage, fins

## 1. Introduction

Demand for energy has never been so high. As society becomes increasingly more dependent on technology, the demand for energy increases more and more each year [1]. With rising energy prices, government incentives and green stewardship initiatives, it is advantageous for most industrial sectors to reduce their energy consumption or optimize their energy cycles [2,3]. For many industries, heat exchangers are a relatively simple and cost-effective way to offset their energy demand by recycling otherwise wasted heat back into their process. However, some processes may not be able to effectively integrate heat exchangers due to several reasons such as cycle time or equipment arrangement which makes it impossible to link two streams [4]. Therefore, a portable heat exchanger or energy storage system could be beneficial for processes looking for a more flexible heat recycling arrangement. A detachable energy storage system could be useful to capture waste heat from a desired process stream and transfer it to another fluid at a later time rather than transferring heat directly and instantaneously.

## 1.1 Energy storage systems

Various types of intermediary energy storage systems have been put in place for decades, from rudimentary pumped water head energy storage to more modern chemical batteries [5]. Latent heat thermal storage (LHTS) occurs when energy is stored during the material phase change. LHTS systems leverage phase-change materials (PCMs) which store energy by absorbing heat and melting at high temperatures, and conversely releasing the stored energy and freezing at lower temperatures. PCMs are commonly used in energy storage devices since they can be tailored to process temperatures by manipulating several parameters such as material and matrix content [6].

PCMs can be integrated into traditional heat exchanger designs. Promising results have been shown for rotary-type heat exchangers [7], plate fin heat exchangers [8,9] and cascading arrangements of PCMs of different melting temperatures [10]. These PCM-modified units can be designed to provide notable heat transfer from fluids; however, their size and

weight requirements means they are not portable [11]. Therefore, there currently exists a gap in design for a portable, removable thermal energy storage system which leverages PCMs.

#### 1.2 PCM

PCMs can be classified into three broad categories: organic, inorganic and eutectics. Some of the most common PCMs are organic based, specifically paraffin. Paraffins are easily tunable due to their alkane nature: compounds in paraffin between 4 and 16 carbons are liquid and chains above 17 carbons are waxy solids at room temperature. The melting temperature of paraffin increases with the number of carbons in the alkanes; however, the latent heat oscillates from adjacent carbons following the same trend [12]. By knowing the composition of the paraffin, it is then possible to determine the physical and chemical characteristics based on its individual compounds. Salt hydrates are an example of an inorganic PCM and are the oldest type of heat storage PCM [13]. These PCMs are composed of a salt and water which crystalize when the material freezes. The latent energy is dependent on the bond strength between the water molecules and the salt. Salt hydrates are notoriously corrosive when compared to organic counterparts and can suffer from phase separation and supercooling [14]. However, due to the simplicity and availability of salt and water, these PCMs are commonly used. Finally, eutectic mixtures can create stable PCMs for compatible materials [15]. Eutectics are interesting as the melting point of the overall product can be manipulated by varying the fraction of each contributing component. Eutectics can be either organic or inorganic [16].

### 1.3 Fins

The addition of fins within the PCM can help accelerate heat transfer since the higher temperature can reach a larger fraction of the PCM. Kamkari & Shokouhmand [17] compared the heat transfer from a vertical wall to PCM using no fins, one, and three horizontal partial fins, and found that adding fins increased the melting rate by 18% and 37% respectively. The trade-off with fin addition is the reduction in total PCM volume which ultimately determines the storage energy. For classical V-fins in a circular enclosure, the heat transfer advantage of thicker fins does not outweigh the loss of heat storage capacity from reduced PCM volume; conversely, extending the fin length is found to increase the heat transfer and outweigh the loss of heat storage [18]. This finding is repeated for other modified angle V-shaped fins and Y-shaped fins which include an additional branch [19,20] Other types of natural fractal and spiral fins have also been found to increase the heat transfer to the PCM at the cost of slightly more complex geometry [21,22].

In addition to thermal conductivity, fin (and container) materials must be compatible with the PCM in terms of reactivity. Cabazzo et al. [23,24] investigated the corrosion resistance of fin and construction metals while immersed in a common salt hydrate PCM. These experiments on a small fraction of the available permutations of alloys and inorganic PCM show that care must be taken when selecting building materials due to variable compatibility.

#### 1.4 Research gap

At the time of publication, no PCM-based heat exchanger design can be considered truly portable, meaning detachable and transportable from one stream to another. This research will model a viable portable PCM-based heat exchanger and storage device which could be employed in process settings. The design is constrained by portability through overall size and weight. In addition, the design must be simple and robust to be attractive for field deployment. The heat exchangers have three fin configurations of nearly identical volumes to eliminate the influence of inequalities in heat exchanger material to PCM ratio in each configuration. Three PCM types will be used to confirm the performance of the fins.

The proposed modelling will attempt to establish the best fin configuration in terms of the three key performance indicators (KPI). The charging and discharging rate will be analyzed temporally by comparing the fraction of solid to liquid PCM during the charging and discharging process for each configuration. The ratio of convective to conductive heat transfer from the heat exchanger will be analyzed as the surface average Nusselt number. Additionally, the time to reach an equal ratio (Nu=1) will be analyzed. Finally, the time to reach equilibrium with the process temperature ( $T_p$ ±1 K for melting or freezing) will be obtained to establish heat transfer in the sensible heating regime once the PCM has completed the phase change.

## 2. Modelling and Analysis

## 2.1 TES configuration

The model for each configuration is shown in Figure 1. Each configuration has an identical outer shell radius of 129.1 mm and height of 302.2 mm with radiused (50/75 mm top and bottom) corners. The central conductive column diameter is 25.4 mm and extends to a height of 250 mm upwards from the base of the shell. The axis of symmetry was directly through the center of the central column. The outer shell is insulated, and the bottom of the central column is subject to a constant process temperature ( $T_P$ ) of 323 K during PCM melting and 288 K during freezing. The initial temperatures ( $T_i$ ) were inverse for each case, so 288 K for melting and 323 K for freezing. The temperatures were selected based on normal ambient air and exhaust conditions in areas where the TES device might be employed. The shell dimension was based on a 20 lb. nominal propane tank which could be recycled into the TES device.

The three fin configurations were designed with nearly identical volumes  $(1.82 \times 10^{-4} \text{ m}^3 \pm 2.5\%)$  to adequately compare their performance. All fins were modelled as circular about the central column. The fins and column assembly were modelled as one solid piece of copper with no fabrication gaps. The volume for the PCMs was identical for modelling (0.009082 m3) for all configurations.



Fig. 1.: Cutaway isometric view of fin Configuration 1, Configuration 2, and Configuration 3.

#### 2.2 Properties of PCM and copper

Three PCMs were selected for this analysis based on their melting temperatures and types. n-Heptadecane paraffin was selected as the organic PCM with a melting point of 22 °C and latent heat of 215 J/g [16]. Calcium chlorine hexahydrate (CaCl<sub>2</sub>\*6H<sub>2</sub>O, shortened to CaCl<sub>2</sub> in text) with strontium chloride nucleating agent was selected as an inorganic PCM with a phase change temperature of 21.4°C and latent heat of 113.2 J/g [25]. Due to this inorganic PCM's recent development, the viscosity was estimated based on other similar inorganic solutions with additives [26]. The commercially available PCM was selected as RT 21 HC with a melting point of 21°C and latent heat of 190 J/g [27]. The physical properties for the PCMs are in Table 1. The physical properties for the copper heat exchanger were taken from the Comsol Multiphysics materials library.

#### 2.3 Modeling basis

The model treated the PCMs as Newtonian fluids and the flow regime was assumed to be laminar. The model took into account buoyancy effects from the melting PCM. A 2D axisymmetrical model was developed to reduce computational time. Throughout the study, the heat will flow from the base of the heat exchanger upwards and radially outwards through the PCM. The PCM will be subjected to melting or freezing, and an interface between solid and liquid

will be seen. The entire TES will be at temperature Ti for initial conditions, which means solidified PCM for the melting case and fluid PCM for the freezing case. For the freezing modelling, the initial conditions dictate no fluid motion.

			PCM		
	Parameter	n-Heptadecane <sup>[16,28,29]</sup>	$CaCl_2 \bullet 6H_2O^{[25,26,30,31]}$	RT21HC <sup>[27,32,33]</sup>	Copper
	Density $\rho_L$ (kg/m <sup>3</sup> )	777	1562	770	
Liquid	Specific heat Cp <sub>L</sub> (J/kg•K)	2300	2250	2000	
Liquid	Thermal conductivity $k_L (W/m \bullet K)$	0.144	0.54	0.2	
	Viscosity µ <sub>L</sub> (Pa•s)	0.00265	0.045	0.00332	
	Density $\rho_S$ (kg/m <sup>3</sup> )	778	1802	880	8700
	Specific heat Cp <sub>S</sub> (J/kg•K)	1850	1900	2000	385
Solid	Thermal conductivity $k_{S}$ (W/m•K)	0.21	1.088	0.2	400
	Melting temperature $T_m$ (°C)	22	21.4	21	
	Thermal expansion $\beta$ (1/K)	9.58E-04	0.001583	0.002333	
	Enthalpy of fusion hf (J/g)	215	113.2	190	
	Transition temperature dT (k)	2	2	2	

The mass, energy and momentum conservation equations govern the melting of PCM in the axisymmetrical model and can be expressed in terms of radial and axial directions [34]:

$$\frac{\partial u}{\partial r} + \frac{u}{r} + \frac{\partial v}{\partial z} = 0 \tag{1}$$

$$\frac{\partial T}{\partial t} + u \frac{\partial T}{\partial r} + v \frac{\partial T}{\partial z} = \frac{k}{\rho C_P} \left( \frac{1}{r} \frac{\partial}{\partial r} \left( r \frac{\partial T}{\partial r} \right) + \frac{\partial^2 T}{\partial z^2} \right)$$
(2)

$$\rho\left(\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial r} + v\frac{\partial u}{\partial z}\right) = -\frac{\partial P}{\partial r} + \mu\nabla^2 u \qquad \text{for radial} \qquad (3)$$

$$\rho\left(\frac{\partial v}{\partial t} + u\frac{\partial v}{\partial r} + v\frac{\partial u}{\partial z}\right) = -\frac{\partial P}{\partial z} + \rho g(T - T_m)\beta + \mu \nabla^2 v \quad \text{for axial} \tag{4}$$

where *T* is the temperature, *t* is time, *k* is the thermal conductivity,  $C_P$  is the specific heat at constant pressure, and *u* and *v* are the radial and axial velocity components. The density is denoted by  $\rho$ , the pressure by *P*, the viscosity force by  $\mu \nabla^2$  in either direction and  $\mu$  is the viscosity. The buoyancy is affected by the thermal expansion coefficient  $\beta$  and driven by the temperature difference with the melting temperature,  $T_m$ . For PCM phase change, the transition zone must be considered between solid and liquid state due to the porous nature of the media. Thus, a term is added for the liquid fraction during phase change [35]:

$$\frac{M(1-f)^2}{f^3+q}, \text{ in either } u \text{ or } v \text{ direction}$$
(5)

where 
$$f = \begin{cases} 0 \text{ for } T < T_m \\ 1 \text{ for } T > T_m + dT \\ \frac{T - T_m}{dT} \text{ for } T_m < T < T_m + dT \end{cases}$$
(6)

In this term, the M is the "mushy" parameter, q is a very small anti-singularity number to ensure continuity, f is a Heaviside function about the transition temperature and dT is the transitional temperature range above the melting point.

The total time for melting or freezing, as well as time until the average surface Nusselt number Nu reaches 1 will be assessed as key performance indicators. The melting time is defined as when the melting fraction of the PCM reaches 1. Conversely, the freezing time occurs when the melting fraction becomes 0. The melting fraction is defined as:

$$MF = \frac{\forall_{Tm+dT}}{\forall_T} \tag{5}$$

where  $\forall_{(Tm+dT)}$  is the volume of PCM above the melting temperature and  $\forall_T$  is the total volume of PCM. The Nusselt number is the ratio of convective to conductive heat transfer and can be defined as:

$$\overline{Nu} = \frac{q''}{(T_P - T_i)} * \frac{H}{k}$$
(6)

where q'' is the normal conductive heat flux on the surface of the find and central column. Using the heat flux at the surface of the copper heat exchanger drives the Nusselt number as a function of heat removal efficiency from the copper to the PCM, whether it be solid or fluid.

#### 2.4 Model solver, mesh, time-step, and validation

The model used a time dependent simulation with heat transfer in fluids and solids coupled with laminar fluid flow. The modelling software was COMSOL Multiphysics version 5.1 which was used to rebuild the 2D CAD model for each configuration, generate the boundary conditions and physics, and build the mesh. The direct solver was MUMPS. The mesh was automatically generated by COMSOL which focused the element density about the model boundaries, mainly the fins.

The model solutions for the governing equations were tested against four mesh sizes to determine the accuracy of the results. The average surface temperature of the PCM over time was obtained for the n-heptadecane melting case of Configuration 3 for these mesh designs and shown in Figure 2. With increasing mesh density, the solution converges at the price of significantly more computational time. Since the aim of the study is to compare several configurations with similar conditions, the normal physics-generated mesh (6348, 8526 and 6398 elements for Configurations 1, 2 and 3 respectively) was used for the model due to the balance of accuracy and computing resources.

A solver timestep analysis was performed to determine if the results were sensitive on time interval. Three timestep schemes (Table 2) were employed to model  $CaCl_2*6H_2O$  melting in Configuration 2 and the resultant average temperature of the PCM was analyzed. The trends show that the overall results were independent of the timestep used in the analysis; thus, the interval could be optimized for resolution and computational time. The modeling employed a 0.5 hour timestep throughout the first 24 hours and 1 hour timestep beyond 24 hours for the melting cases. For the freezing cases, the first 60 hours had a 0.5 hour timestep with additional length being modelled with 1 hour timestep.



Fig. 2: Average temperature of the PCM as a function of time for n-heptadecane melting in Configuration 3 for mesh densities of 2419, 3674, 6398, 9536 mesh elements, respectively.

Table 2. Timestep sensitivity analysis for melting of calcium chloride hexahydrate in Configuration 2.								
	Times	step (h)	Average temperature (K)					
Interval (h)	0-2	2-24	1	2	4	8	16	24
Scheme 1	0.125	1	291.6	293.1	294.5	296.3	310.1	320.2
Current model	0.5	0.5	291.6	293.1	294.5	296.3	310.1	320.2
Scheme 2	1	2	291.6	293.1	294.5	296.4	310.3	320.2

The numerical model was used to replicate and compare the results with Shmueli et al. [35]'s experiment regarding the melting of RT27 from Rubitherm GmbH. The current numerical model was used with the experimental parameters to analyze the melting fraction at various points. The results were compared against Shmueli as well as Ebadi et al. [35,36] who also used the experiment to validate their results.

Figure 3 shows numerical model agrees with the results from previous works. Qualitatively, the model results agree more with the original figures from Shmueli [35]; however, the numerical models all show the same physics that are to be expected with the melting of PCM. Based on the comparison from these previous works, the model appears to be valid for PCM phase change modelling.



Fig. 3: Validation of current model (rightmost) against previously published works for melted fraction of RT27 at several times

## 3. Results and discussion

The results of the TES modelling are presented and interpreted within. For the melting simulations, the time to complete liquidation, time to Nusselt = 1, and time to  $T_p$ -1 K were obtained. For the freezing simulations, the time to complete solidification, time to Nusselt = 1, and time to  $T_p$ +1 K were evaluated. The melting or freezing fraction at several intervals for each configuration and PCM were also observed.

#### 3.1 PCM melting

For the melting case, the initial TES system temperature was 288 K with the process temperature being 323 K. The melting fraction was obtained by performing a volume integration of the model for nodes with a temperature at or above melting and dividing by the total PCM volume and reported in Table 3.

The melted fraction, average Nu and temperature of each PCM as a function of time for each fin configuration can be seen in Figure 4. As shown by the plot, the PCM has a greater effect on performance than the fin configuration, with RT21HC reaching full melting faster than the other PCMs. In terms of fins, Configuration 2 yielded faster melting for each PCM when compared with the other fins. For the average surface Nusselt number, the three PCMs also exhibit different behaviors due to their physical properties. Calcium chloride hexahydrate has the lowest but steadiest ratio of convective to conductive heat transfer, while the other PCMs have a higher number before dropping off steeply. Comparing fin configurations, Configuration 2 shows the quickest drop in Nu which is consistent with the faster melting fraction observation. The average temperature of the PCM, both solid and liquid, was also determined for each configuration as a function of time. The final melting time was obtained when the average temperature of the bulk PCM was 322 K.

Menteu Haction (70).					
	Melted fraction (%)				
Time (h)	1	2	3		
1	5.	6.	5.		
1	9	1	9		
4	2	2	2		
4	0.2	6.6	7.1		
0	5	6	5		
0	4.7	6.3	8.5		
10	8	9	8		
12	4.9	8.4	7.8		
16	1	1	1		
10	00.0	00.0	00.0		

Table 3. Melted fraction (%) for n-heptadecane melting at various times for three configurations Melted fraction (%).

The temperature plot shows the temperature of the PCM maintaining a steady slope during PCM phase change before rapidly gaining heat once most of the volume becomes fluid. The temperature eventually reaches an asymptotic trend towards the process temperature since the walls are insulated. As observed with the liquid fraction, each PCM operates at slightly different heating rates due to their physical properties. In terms of fin configuration, Configuration 2 appears to result in the highest heating rate for each PCM.

#### 3.2 PCM Freezing

For the freezing case, the PCM initial temperature was 323 K while the process temperature was 288 K. The melted fraction of PCM was obtained by performing a volume integration of the model for nodes with a temperature at or above melting and dividing by the total PCM volume and reported in Table 4.

Figure 5 shows the melted fraction, average *Nu* and temperature of all PCM and fin configurations during freezing. For freezing, the calcium chloride hexahydrate appears to be much slower to freeze in comparison with the other PCMs.

Similar to the melting case, Configuration 2 yields the fastest freezing of the overall volume for each PCM. The trends for Configurations 1 and 3 show noticeable nodes which could be associated with the heat transfer around the fins as the process temperature reaches a fin height and follows along radially. This may be less pronounced in Configuration 2 as the angled fins are oriented upwards towards the warmest temperature of the volume.

	Melted fraction (%)			
Time (h)	1	2	3	
1	99.9	99.9	99.9	
5	97.5	98.2	94.6	
10	53.5	39.8	56.0	
15	14.5	0.0	18.4	
20	0.0	0.0	0.0	

Table 4. Melted n-heptadecane fraction (%) during freezing for three fin configurations Melted fraction (%)

Fig. 4: Melted fraction, average Nu, Average temperature of PCM (n-heptadecane, CaCl<sub>2</sub>, RT21HC) during melting for each fin configuration (1, 2, 3).





For each configuration and PCM, the Nusselt number reaches a peak within 2 hours and gradually tails off for the remainder of the melting process. Calcium chloride hexahydrate is the first PCM to reach a dominant conduction heat transfer state. Since the melted fraction of the PCM is already on top of the solidifying region, convective heat transfer is hampered and is soaked rather rapidly compared to the melting case. Once again, the PCM type seems to dominate the overall trends. The average PCM temperature for both solid and liquid PCM during the freezing process in each configuration. The initial heat release to the heat sink appears dependant on the PCM type with calcium chloride hexahydrate being the slowest to release heat. Configuration 2 appeared to have only a slightly better heat transfer rate based on the slopes.



Fig. 5: Melted fraction, Nu and temperature of PCM (n-heptadecane, CaCl<sub>2</sub>, RT21HC) during freezing as a function of time for each fin configuration (1, 2, 3).



## 3.3 PCM melting result analysis

The three KPIs were used to statistically compare the performance of each fin configuration. The total time to reach each indicator were analyzed using the Minitab17 statistical software. The results were plotted for normality to ensure the datasets were consistent. Each KPI was tested against the PCM and configuration in an ANOVA to determine the result weighting. Then, each KPI was individually tested against the PCM type and configuration in a one-way ANOVA to determine if the differences in means were significant. The time values for each KPI for melting are summarized in Table 5.

			Time (h)	
Configuration	PCM	Liquification	Nu = 1	$T_{avg PCM} = 322 K$
1	n-heptadecane	14.75	24.25	25
2	n-heptadecane	12.25	21.5	22.5
3	n-heptadecane	14.5	23.25	24.75
1	CaCl <sub>2</sub> •6H <sub>2</sub> O	14.5	24.25	31
2	CaCl <sub>2</sub> •6H <sub>2</sub> O	14	23.5	30
3	CaCl <sub>2</sub> •6H <sub>2</sub> O	15	24	32
1	RT21 HC	11.75	18.75	20.25
2	RT21 HC	10	16.25	17.5
3	RT21 HC	11.75	18.5	20

Table 5. Key performance indicators for fin configurations during various PCM melting

For the melting case, the PCM had a much greater effect on performance for all parameters than the fin configuration. The PCM type had a significant effect on the melting time (p=0.010), average Nusselt number (p=0.001) and average PCM temperature (p=0.001) for  $\alpha$ =0.05. For the same KPIs, the configurations had no significant effect on mean time (p=0.678, p=0.754, p=0.877).

#### 3.4 PCM freezing result analysis

Like the melting case, the three KPIs were used to statistically compare the performance of each fin configuration. The results were checked for normality to ensure the datasets were consistent. Each KPI was tested against the PCM and configuration in an ANOVA to determine the result weighting, then individually tested against the PCM type and configuration in a one-way ANOVA to determine if the differences in means were significant. The time values for each KPI for freezing are summarized in Table 6.

Table 6. Key performance indicators for fin configurations during various PCM freezing.						
			Time (h)			
Configuration	PCM	Solidification	Nu = 1	$T_{avg PCM} = 289 K$		
1	n-heptadecane	18.25	60.75	140.75		
2	n-heptadecane	13.5	40.25	145.5		
3	n-heptadecane	19	55.25	170.5		
1	CaCl <sub>2</sub> •6H <sub>2</sub> O	28.5	17.5	116.5		
2	$CaCl_2 \bullet 6H_2O$	21	13.5	105		
3	$CaCl_2•6H_2O$	29.5	17.5	119.25		
1	RT21 HC	15.5	55.75	158.25		
2	RT21 HC	11.75	36.5	162.75		
3	RT21 HC	15.5	52.75	185.5		

Based on the statistical analysis, the PCM had the greatest effect on performance versus the configurations. The PCM had a significant effect on the total freezing time (p=0.011), time to Nu=1 (p=0.004) and the time to reach Tp+1 (p=0.006). Conversely, the fin configuration had no significant effect on the same KPIs (p=0.504, p=0.662, p=0.635) for  $\alpha$ =0.05.

#### 4. Conclusion

The performance of three novel PCM TES was studied using numerical modelling and key performance metrics for charging (melting) and discharging (freezing). Three PCMs were used in each configuration to establish trends between said configurations. The key performance indicators were selected as metrics that are easily interpreted and repeatable for further TES development. The following conclusions can be drawn from the study.

The PCM had the greatest impact on KPIs due to the variability in physical properties. The differences in the physical properties, especially when applying phase change, has a great impact on the overall TES design and performance even further than the KPIs studied within.

While the configurations had no statistical significance in terms of performance, qualitative observations show some potential for improvement based on the proposed fin geometries. For almost all cases, Configuration 2 with upward slanted fins showed the best performance based on the KPIs. Further work leveraging these preliminary findings could produce a more favorable configuration.

The TES configuration in general can be optimized to yield better sensible heating. Though the TES shows promise in terms of total charging and discharging time, the sensible heating and cooling time to the process temperature is quite long.

The fins were configured for increased fluid motion while a heat gradient is applied, however it can likely be improved for better contact with the PCM volume for low thermal gradients.

The overall charging and discharging times, as well as the modelled process and initial temperatures, indicate that this type of TES could be employed as a portable heat exchanger in mobile field application where direct heat exchangers are not considered. The relatively small size of the unit would make it ideal for a passive application where heat would not normally be recovered, such as low-grade exhaust ducts, or hard to reach areas. Once charged, the PCM could simply be left in place or transferred to another low-grade heating application without much work. The lack of moving parts is also considered an asset in terms of maintenance time and cost.

#### 5. Acknowledgements

The author acknowledges the help and insight provided by co-authors during the conception and execution of the design. The author would also like to thank his team at Savron for supporting him during his studies and the completion of this project.

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