Building a heat battery for domestic applications

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***Abstract*—A solution to use domestic heat energy more efficiently is the addition of a heat battery to a boiler. The heat battery contains a phase change material (PCM), with low conductivity and high specific heat, and can store the residual heat energy efficiently. Paraffin wax is a suited material for this application because of its high latent heat storage. However, the low conductivity of paraffin wax is a problem in terms of storage time. In this research, a finned tube was used to tackle this problem and there has been investigated if the heat battery could be suited for a domestic application. To measure the effectiveness of the finned tube a numerical model and an experiment were designed. In this experiment, a water source, adjustable in temperature and flow rate, was connected to a tube with no fins and the finned tube. The temperature and heat flux were measured to look at the effect of the fin structure. This was also done in the numerical model to compare the results. The results showed that with the finned tube it took about 60 minutes to extract the heat from the PCM whereas with the tube without fins it took almost five hours. From these results can be concluded that this method is promising but not yet good enough to be used in a domestic application.**

I. Introduction

One of the biggest problems the world is currently facing is climate change. The world population grows exponentially and so does the demand for energy and heat storage [1]. One solution is to make energy sources more sustainable such as the use of solar boilers and geothermal heat. On the other hand, heat generated can also be used more efficiently especially in terms of storage [11]. The usage and storage of energy in a more efficient way has therefore become of increasing international importance [5].

A solution to deal with heat more efficiently is to raise the efficiency of a boiler by addition of a heat battery. In a boiler, the water is constantly held at a high temperature to contain a lot of thermal energy. To illustrate this, a kitchen boiler of about 10 liters contains approximately 1600kJ of energy. This thermal energy is unused most of the time and will slowly dissipate to the environment. A heat battery on the other hand contains a Phase Change Material (PCM) in which this energy can temporarily be stored and later released from again by changing phase. The special properties of a PCM make it possible to reduce the total difference in temperature needed. For example, when 1 kg of a PCM like paraffin wax undergoes a phase change about 180 kJ of thermal energy is released. With this amount of thermal energy 1 kg of water can be raised more than 40°C. [16]. Van der Stoel's research has shown that paraffin wax is one of the PCM's that fits the application of a heat battery best [16]. The main problem with paraffin wax is the low thermal conductivity, which makes the heat transfer very time-consuming. Paraffin wax is only suited for this domestic application if it is possible to extract the heat from it within 15 minutes. To this day is not possible to release energy in such a short amount of time. As the storage may take a little longer it is especially important to look at the solidification process. The heat transfer through a material can be raised in several ways. First, it is possible to raise the thermal conductivity by the addition of nanoparticles of a material with higher conductivity. When, for example, small aluminum particles are added to the PCM, the overall thermal conductivity will increase [3]. Additionally, a fin structure can be added. The addition of a fin structure made from a material with high thermal conductivity enlarges the surface area and ensures the heat conduction to be increased [4]. The use of fins and nanoparticles has been investigated both separately and combined. From this research, it was found that for melting as well as for solidification PCM the use of only fins resulted in the most significant improvement [8] [9]. Another additional problem with the nanoparticles is the sedimentation of the particles [7]. Two other techniques used in previous research to increase the heat transfer were the use of a heat pipe network [15] or metal foams [6].

Fig. 1. Spirotube

The objective of this research was to raise the heat flux to, and from the paraffin wax, and shorten the process of heat transfer so it can be used in a domestic application. A finned copper tube, a Spirotube, seen in figure 1 was used to accomplish this. The addition of fins will increase the contact surface with the PCM and therefore the heat flux. This objective has led to the following research question: 'What is the effect of a fin structure on the thermal energy storage in a heat battery of paraffin wax-based phase change material for domestic applications?' This study hypothesized that by the addition of a fin structure, and thus the surface area, the overall heat flux of the heat battery would increase. Therefore the PCM would be able to release the heat to the water fast enough to be used in a domestic application.

The research question got tackled in two parts. First of all, a numerical model based on a literature study was made in MATLAB to provide theoretical insight on the subject. The numerical model was used to validate the experiments that have been done in the lab. In these experiments, warm and cold water was led through a Spirotube, and a regular tube, with a paraffin wax shell. In these experiments, the heat flow, run time, melting border, and temperature were measured. This was done with the information given of the water source and the use of thermocouples.

The structure of the paper is as follows: in section II the theory behind the heat battery will be explained and the numerical model will be discussed. In section III, the methodology of the experimental research and the test setup will be discussed. The results of the experiments can be found in section IV, the results. These results will be followed by the discussion in section V, in which both the experimental work as well as the numerical model are critically reviewed and the results put in perspective. The paper ends with sections VI and VII, the conclusion, and recommendations for potential follow-up research.

This research has been conducted as part of the Bachelor End Project for Mechanical Engineering students at the TU Delft in the third Bachelor year.

II. Theory

TABLE I
PROPERTIES

Symbol	Property	Unit
Q	Thermal Energy	J
c_p	Heat coefficient	J/kg K
m	Mass	kg
$\dot{m}$	Flow rate	kg/s
T	Temperature	°C
ΔT	Temperature difference	°C
h	specific enthalpy	kJ/kg
Δh_{latent}	Latent heat	kJ/kg
T_o	Start temperature	°C
T_f	Final temperature	°C
T_m	Melt temperature	°C
ΔT_m	Melting range	°C
ρ	Density	m^3/kg
t	Time	s
Fo	Fourier number	-
k	Thermal conductivity	W/m K
q	Heat flux	W/m^2
A	Area	m^2

A. Background theory

The goal of a heat battery is to store and release thermal energy with the use of a phase change material (PCM). Therefore a distinction will be made between two different types of thermal energy storage, sensible heat storage (SHS) and latent heat storage (LHS). Sensible heat storage occurs when a material is heated. This causes an increase in temperature which follows the equation:

$$Q_{SHS} = c_p m \Delta T \tag{1}$$

In a PCM the sensible heat storage takes place until the phase change occurs. During a phase change, the PCM will remain at an almost constant temperature while heat energy is still transferred into the PCM. This is called latent heat storage. The theoretical latent heat stored in this phase change follows the equation:

$$Q_{LHS} = m \Delta h_{latent} \tag{2}$$

When the phase change has finished sensible heat storage continues. This results in the theoretical total heat storage equation [16]:

$$Q = mc_p(T_m - T_o) + m\Delta h_{latent} + mc_p(T_f - T_m) \tag{3}$$

With this equation, the total heat energy stored in or released from the PCM can be calculated. In practice, most PCM's have no real melting point but a melting range. This means the latent heat storage process occurs over a temperature range. Nevertheless, the total amount of latent heat stored is the same. This theoretical process of heat storage is depicted in figure 2. The slope of the graph in the sensible range is equal to the specific heat capacity, which is assumed equal in solid and liquid phase [16].

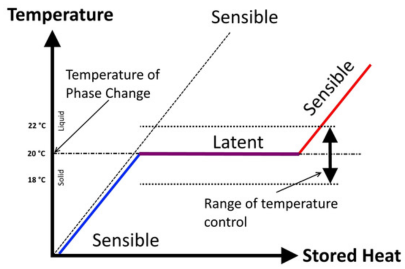

Fig. 2. Sensible and latent heat over temperature and stored heat [14]

Another important aspect of the heat battery is the heat transfer rate from and to the PCM. The model used only takes conduction into account since radiation and convection are almost negligible within the PCM. As paraffin wax has a very poor thermal conductivity, the heat transfer may be a slow process. The theoretical rate at which heat transfer occurs in a material through respectively one-dimensional and two-dimensional conduction are based on the equations [10]:

$$\rho c_p \frac{\partial T}{\partial t} = k \frac{\partial^2 T}{\partial x^2} \tag{4}$$

$$\rho c_p \frac{\partial T}{\partial t} = k(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2}) \tag{5}$$

With the use of the Finite-Difference Method, these differential equations are converted to numerical equations, this will be discussed in the next section. Apart from the heat transferred over the surface of the tube, it is possible to further increase the heat transfer. The best one applicable and most efficient one being: increase the surface area with the use of fins[8] [9]. Thereby realizing a tube with fins on its outer surface, the Spirotube figure 1. The surface area scales linearly with the heat transfer in the equation:

$$\dot{Q} = qA \tag{6}$$

The shape and the thermal energy transfer of a Spirotube are very complicated to simulate. The complex structure can be seen in Figure 1. However, it makes mainly use of a fin structure which can be simplified and simulated to understand how the fin structure conducts the thermal energy to the PCM. This will be used in the numerical two-dimensional model.

B. Numerical model

1) Equations: A numerical model was made in *MATLAB ver. R2020a* to apply the background theory and to compare it to the test results. The model aims to provide a simulation of how, and at what rate, the heat transfer would take place in the setup based on the equations from section A. This was done in a two-dimensional model where instead of thermal energy the specific enthalpy 'h' in kJ/kg was used to measure the thermal energy stored in, and released from the PCM. The Finite-Difference Method for two-dimensional unsteady conduction was used to model the heat transfer. As described in Mills (Section 3.5.2) it is *a method in which the spatial and time coordinates are discretized to form a mesh of nodes. This with the use of dx and dy to discretize distance, and dt to discretize time. After that, finite-difference approximations are made of the derivatives that appear in the heat conduction equation to convert the differential equation to an algebraic difference equation* [10]. The general equation used is from Mills table 3.9 Item 1 [10]:

$$\begin{aligned} T^{i+1}_{m,n} =& Fo_x(T^i_{m-1,n} + T^i_{m+1,n}) + Fo_y(T^i_{m,n-1} + T^i_{m,n+1}) \\ &+ (1 - 2Fo_x - 2Fo_y)T^i_{m,n} \end{aligned} \tag{7}$$

With:

$$Fo_x = \frac{\alpha \Delta t}{\Delta x^2}, \quad Fo_y = \frac{\alpha \Delta t}{\Delta y^2}, \quad \alpha = \frac{k}{\rho c_p} \tag{8}$$

The Fourier numbers are limited by the critical time step which is the relation between Δx/Δy and α and gives the largest time step that can be used. At the borders of the PCM, a few boundary conditions were used according to items 3 and 4 from table 3.9 in Mills[10].

The sensible heat storage and latent heat storage in kJ/kg are modeled respectively with the equations:

$$h_{SHS} = c_p \Delta T \tag{9}$$

$$h_{LHS} = \int_{T_m,start}^{T_m,finish} [c_p + \frac{\Delta h_{latent}}{\frac{\Delta T_m}{2}\sqrt{2\pi}} e^{-\frac{(T-T_m)^2}{2(\frac{\Delta T_m}{2})^2}}]\ dT \tag{10}$$

As shown in equation 10 the latent heat is modeled with the use of a Gaussian function to model the change of cp over the desired temperature range. This results in a peak in melting or solidification. This causes the specific enthalpy to rise or decay significantly while the temperature changes very little, until all the latent heat, has been transferred. The area under the curve of the Gaussian function is equal to the total latent heat in kJ/kg.

The fins are incorporated into the rest of the model by assigning certain nodes in a horizontal row a constant temperature while the rest of the nodes follow the normal conduction equations. This creates the fins in the mesh of nodes. The constant temperature of the fins is equal to the temperature of the center tube and helps to conduct the heat energy into the PCM.

2) Assumptions: In the numerical model, several assumptions were made which will be discussed in this section.

TABLE II
PROPERTIES PARAFFIN WAX

Property	Value	Unit
c_p	2100	J/kg K
k	0.2	W/m K
Δh_{latent}	180	kJ/kg
ρ_{par}	780	m^3/kg
ΔT_m	52-56	°C

The largest assumption made in the model is that the whole Spirotube, fins included, is considered to be at a constant temperature. This applies to the Spirotube with the assumption that the water flows at a sufficiently high rate to realize a constant temperature over the whole Spirotube. The high conductivity of the Spirotube enables the thermal energy to be equally conducted to every part of the Spirotube both in storage and release. Additionally, is the assumption used that the whole system is adiabatic, thus no losses to the surroundings.

Another assumption is that the material properties of the paraffin wax were taken as a constant instead of a variable over temperature or other parameters. The thermal conductivity and the density of the paraffin wax were assumed to be constant instead of temperature-dependent, and the specific heat capacity of the paraffin wax was assumed to be not phase-dependent. Only in the latent range, the specific heat capacity changed temporarily as explained earlier. Furthermore, the latent heat energy that can be stored in the paraffin wax was assumed to be a fixed value while in reality, it is in the range of 170-190 kJ/kg.

A few other physical phenomena which were not incorporated into the model are: The flow behavior of the PCM in the liquid phase in terms of convective heat transfer, the volume change of the paraffin wax after phase change and the effects of gravity. Furthermore, only heat transfer through conduction has been taken into account and the complex structure of the Spirotube is simplified into a tube with simple fins in the model. Finally, the model is two-dimensional while the reality is three-dimensional, so any three-dimensional effects have not been taken into account. The heat transfer in a three-dimensional model would likely be different as well as the effects of the fins in a volume.

3) Numerical model results: The final model was chosen to simulate the release of the thermal energy from the paraffin wax. This was done because the rate at which this happens is most interesting in relation to the research goal. The storage of heat is a less important factor as this is allowed to take a longer time in the application of the heat battery. The experiments were also mainly focused on the release of thermal energy from the wax. To model the effect of the fin structure, both a model with and a model without the fin structure were made. This gave the results presented below.

First of all, figure 3 shows, the PCM in the model without the fin structure takes about 22.000 seconds to release its heat and cool down to 20 °C, which is equivalent to about 6 hours. Figure 3 shows the model applied with the fin structure which takes about 1000 seconds, equivalent to about 17 minutes. Furthermore, can be seen in figure 3 that the temperature curve over time is very much as what was expected from the theoretical background. The curve starts with an almost constant slope downwards until it undergoes a phase change when the latent heat is released and the temperature only slightly increases. After the phase change the temperature decreases again until the minimum temperature of almost 20 °C is reached. Close to the minimum temperature the slope grows closer to zero again due to the smaller temperature differences. The total specific heat released at this point in the model is about 285 kJ/kg. Multiplying the total specific heat released with the mass of the PCM in the setup, which is a little more than 3 kg, gives a total stored energy of about 900 kJ.

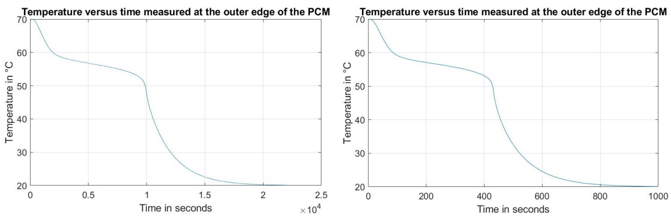

Fig. 3. Temperature change over time in the numerical model without fin structure (left) and with fin structure (right) measured at the outer edge of the PCM. Note that the timescale is different for both figures.

The temperature curve in two dimensions is modeled in a surface plot in figure 4 at four-time instants in the melting process. This is meant as a support to show how the temperature changes in the PCM over time and to illustrate the temperature distribution.

III. EXPERIMENTS

To validate the numerical model an experiment was designed, this can be seen in figure 5. To recreate a heat battery, a Spirotube with an outer diameter of 65 mm was vertically placed in a PMMA tube with an inner diameter of 74 mm. To show the effect of the fin structure the same experiment was performed with a regular copper tube. The used PCM in the

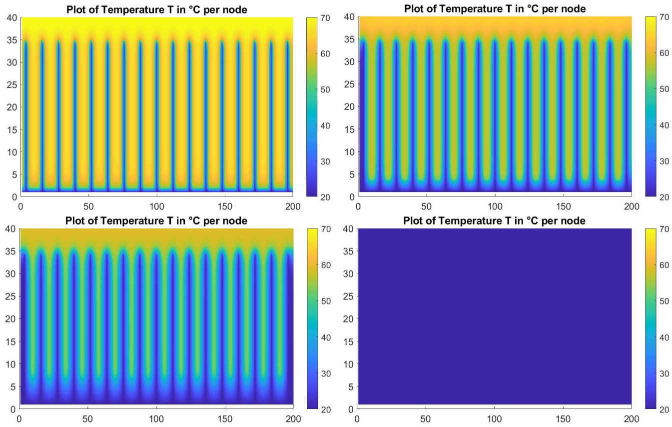

Fig. 4. Temperature PCM in 2D surface plot at t = 10,50,100 and 1000 sec

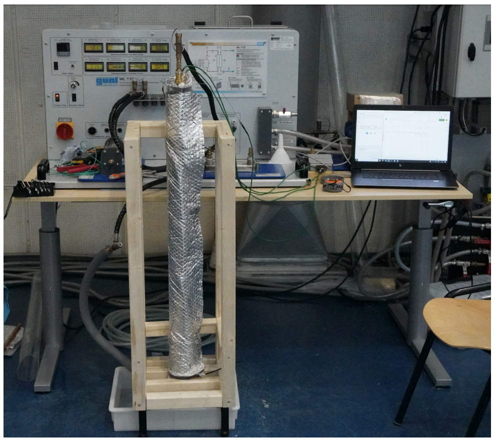

Fig. 5. Experimental setup

setup was paraffin wax of type Sasolwax 0716, and was placed around the Spirotube in the PMMA tube. To make the setup watertight a PMMA cap was installed at the bottom and the entire setup was placed onto a wooden frame. This setup gave the chance to simulate a real heat battery being connected to a water source. In this configuration, the flowing water was able to transfer heat into the paraffin wax and the other way around. The paraffin wax was melted and solidified by running water through the Spirotube with the use of the water source. The melting process was done until the whole PCM was liquid. The solidification process was done until the whole PCM was at room temperature. The water source used was a GUNT WL-110 cooling and heating bath thermostat. An advantage of this water source was its ability to measure and control the inlet temperature and flow rate. To measure the temperature change over time, four K-type thermocouples were placed in the tube at different heights. The temperature was measured over time by a 1E018E4 MyDAQ of National Instruments. The setup was surrounded by a removable insulation casing. The main goal of the experiment was to measure the phase change behavior and temperature change of the paraffin wax over time when just a copper tube with no fins was used versus the use of the Spirotube. This was done both visually with a camera and experimentally by measurements of the temperature difference between the in and outlet, the flow rate, the melting front height, the temperature at different heights, and the run time.

To rule out as many external factors as possible and produce reliable results a few design requirements were drafted:

1) The setup needs to be oriented vertically with an open top. This is the easiest way to absorb pressure differences due to thermal expansion and leakage is minimized. Furthermore, the fin structure of the Spirotube is always used optimally in this position.
2) When the Spirotube is heated the water should enter at the top and leave at the bottom of the setup. When cooling, this should be switched. This is because, when the wax is melted it will expand and the other way around. When the tubes are not attached correctly, high pressure might arise at the bottom. Taking the height of the melted paraffin wax into account it must be at least 10 cm below the top of the PMMA tube, because of an expansion of about 10% when melted.
3) The tube needs to be transparent, so the melting process can be observed visually.
4) The Spirotube needs to be positioned in the middle of the PMMA tube to provide reliable measurements at every location in the wax.
5) The temperature is measured at the outer border of the wax as the wax melts/solidifies the slowest at the border. Besides, the thermocouples must be placed at that position without the fin structure troubling the measurements or influence accurate placement.
6) The PMMA tube needs to be insulated against radiative and convective heat losses to minimize the heat transmitted to the surroundings.
7) The flow rate from the water source needs to be constant over time to compare the results of different measurements.

In the experiments, the heat flow was estimated with the difference between the in- and outlet temperature and the flow rate. This should provide a general idea of how much heat was transferred. When hot water flows through the Spirotube the wax is expected to melt from the top. A melting front therefore develops from top to bottom. This melting front can be measured with a tape measure. In addition, the temperature can be measured at different heights in the setup.

A water source was used that can run water with a maximum of 70 °C and a minimum of 20 °C through the Spirotube. The water source is also able to measure the in- and outlet temperature and adjust the flow rate. The flow rate and temperatures could be read off the water source itself. With the assumption that the specific heat of water is constant at 4186 J/kg K, the heat flow could be estimated. This could be done with the use of the equation:

$$\dot{Q} = c_p * \dot{m} * \Delta T \tag{11}$$

The measurements were done until the difference between the inlet and outlet temperature was negligible. During the first 20 minutes, the measurements were done every 2 minutes and after 20 minutes the measurements were done every 10 minutes. After 20 minutes the temperature change over time became a lot smaller, therefore larger intervals between measurements were accurate enough. To measure temperature at different heights in the wax thermocouples were used. This way the temperature could continuously be measured at various locations in the configuration. The height of the melting front was measured from the bottom of the PMMA tube until the place where the paraffin wax started to get transparent.

To validate the results of the experiments it was important to take the accuracy of the measurement methods into account. The accuracy of the thermocouples is 0.5 °C or K [12]. There is also a small tolerance in the exact location of the thermocouples in the tube. A small difference in the positioning of the thermocouples affects the results of the measurements. The thermocouples have a diameter of 1 mm between the outer diameter of the Spirotube is 65 mm and the inner radius of the tube 74 mm. This gives the location of the thermocouples a tolerance of 4.5 mm.

IV. Results

First, the heat flux over the entire Spirotube is shown for the solidification process, followed by the melting front development over time. This section will end with the results of temperature measurements in the Spirotube at different heights.

A. *Heat flow Spirotube*

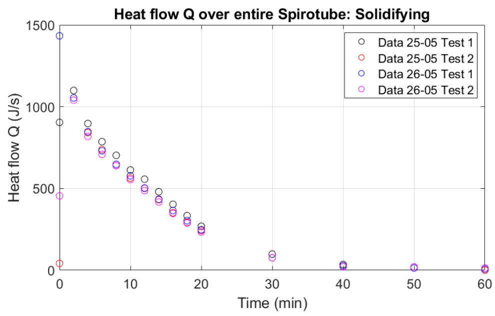

Fig. 6. Heat flow over time

Figure 6 shows the heat flow estimated at different time points in the solidification process. The water flow rate was kept constant at 1 L/min in all experiments and the results of the four different measurements look very similar. The heat flow shows a decreasing gradient and the difference between the inlet and outlet temperature got smaller over time. After 20 minutes the temperature difference decreases rapidly. At this point, the temperature between the wax and the water was small thus only a little heat was transferred. In the melting process, the same results were seen but the heat flow decreased slower over time. The area under the four graphs of figure 6 showed that the total energy absorbed by the water during solidifying of the wax in 60 minutes was about 940 kJ, 820 kJ, 890 kJ, and 830 kJ. Within 15 minutes most of the energy, about 70%, was released in all experiments.

B. Melting front results

The melting front was measured over time by taking a picture of the melting front every 10 minutes. The melting front developed from the top to the bottom was observed. Some of these pictures are included in figure 7 and illustrate the melting process. As can be seen from the pictures, in the first 40 minutes the outside PCM showed no signs of melting. In the next 40 minutes, the melting front started to develop. Near the end of the melting process, the decrease of the melting front slowed down, and melting the remaining PCM took significantly more time or was not even possible. The solidification process was more accessible to the eye because of the transparent liquid state of the paraffin wax. Figure 8 shows that the solidification progress is the fastest near the bottom of the configuration. The paraffin wax close to the fins solidifies much faster than the wax further away from the fins. The solidification process showed that the outside of the PMMA end of the copper tube solidified first and from bottom to top.

Fig. 7. Melting border at t = 40min, 50min, 60min, 80min ,90min

Fig. 8. Detailed photo of solidification process

C. Temperature at different heights results

The temperature was measured at different heights. Three thermocouples were used to measure the temperature during melting and solidification at T1 = 45 cm, T2 = 60 cm, and T3 = 70 cm. The heights of the thermocouples were measured from the bottom of the tube. The temperature T4 at 80 cm was eventually left out because of its wrong placement close to a fin. Figure 10 illustrated the temperature over time with the thermocouples placed at different heights during the experiment. In this figure, it is also clearly illustrated that the thermocouple placed closest to the top melted the fastest and solidified the slowest. Figure 9 illustrates different measurements at the same heights. In the first part of the graph, the temperature rises fastest. Around 55 °C the curve starts to flatten, this is in the melting range of the paraffin wax. Thereafter, the temperature curve starts to rise again. The melting process showed similar progress but only reversed. The only significant difference was the run time to achieve the same temperature difference. It took around 60 minutes to solidify all the paraffin wax with a Spirotube, and 90 minutes to melt. The use of just the copper tube gave much longer run times. Solidification of the PCM took at least 5 hours. Melting all of the PCM was not achieved during this research due to run time limitations. After 8 hours the thermocouples had measured an increase of only 20 degrees and the paraffin wax was not even close to the phase change temperature range.

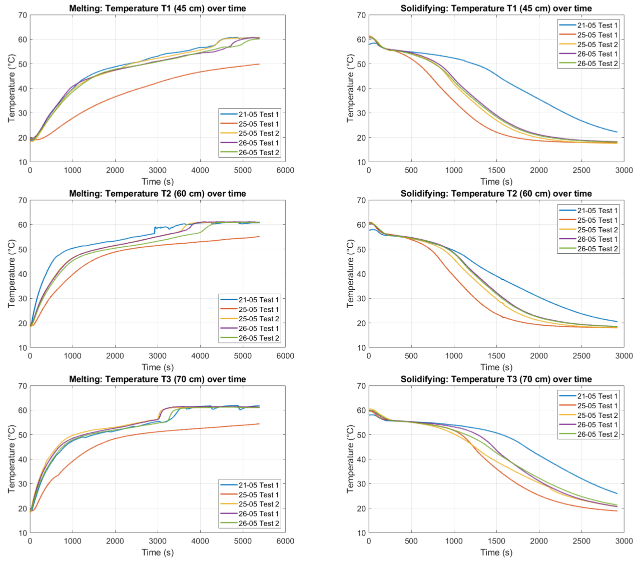

Fig. 9. Temperature over time melting vs solidification

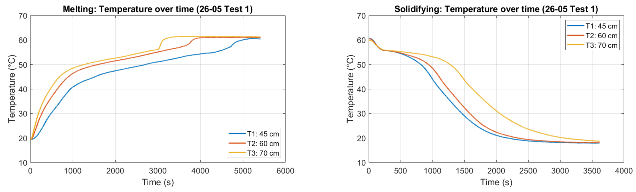

Fig. 10. Solidification melting: 26-05 Test 1

V. Discussion

The result of this research shows the effect of the addition of a Spirotube in a PCM configuration. From both the numerical model, as the experiment conducted, it seems that the Spirotube highly enhances the heat flux with the use of its fins. This is in line with research in the past where the heat flow is researched with an adaptation of fins [8] [9]. Another expected observation was the cascading ascent of the temperature of the PCM. When the temperature had reached the solidification point, around 55°C, the temperature in figure 10 started to flatten. This is because of the latent heat that is transferred from the PCM, which is in line with the background theory provided on latent heat storage in Figure 2 and equation 3.

Furthermore, it can clearly be seen in figures 10 and 9 that the thermocouple closest to the inlet heats faster than the ones further away. This is because hot water entered from the top of the tube. Cool water entered at the bottom of the tube which gave the opposite result during solidification, see Figure 10. The temperature profile over time and the development of the melting boundary correspond with the research of M. Akgün [2] and Righetti [13]. However, the numerical model showed that the temperature profile at every point in the tube was the same.

Considering the domestic application, the run time was measured and compared to the numerical model. The numerical model expected all heat energy to be extracted within 17 minutes. The experiment showed about 60 minutes were needed to extract all of the heat energy. Even though the numerical model provides a good insight in how the solidification takes place, the difference between the numerical model and the experiment is quite significant. This can be explained by the assumptions made in the model as described in the assumption subsection, but mostly due to the way the numerical model was designed. First of all, the model did not make use of the third dimension. This results in a simplification of reality as the spherical configuration of the setup is not correctly modeled. In addition, in the model, a full adiabatic system was assumed. In the experimental setup, which was hard to insulate very well, the system was not adiabatic. However, most importantly the Spirotube was assumed to have a constant temperature over the entire length that did not change over time. This meant that all heat transferred into, or from, the paraffin wax does not change the temperature of the Spirotube. In practice, this is not realistic as the Spirotube is not able to transfer the heat that quickly, and the flowing water is not able to keep the whole Spirotube constantly at the same temperature. This is in line with the melting front observed in the experimental work which indicated that the temperature was not constant over the entire length of the Spirotube. Therefore, this assumption turned out to be inaccurate.

Another interesting result was the difference in solidification time compared to the melting time in the experiments. In the numerical models considered it was also visible that the solidification process was faster. This can be explained by the fact that the melting range is closer to 70 °C than to 20 °. This results in the fact that the heat flow in the melting range is higher in the solidification process compared to the melting process due to the greater temperature difference. Thus, the latent heat is released faster than it is absorbed in the setup used. In addition, the setup was not perfectly insulated, which could have had a positive effect on solidification and a negative effect on melting time due to losses.

To further put the results in perspective for domestic application, the water needed is considered. For the extraction of the energy, thus the solidification of the PCM, a constant water flow rate of 1 L/min was used with a constant inlet temperature of 20°C. The total solidification time of all the PCM was 60 minutes. This means that 60 liters of water with a constant temperature of 20°C has been used to solidify the paraffin wax. In a domestic application, the heat battery will be used in addition to a boiler. A small boiler used in a kitchen has only a volume of 10-15 liters. The graph in figure 6 indicates that in the first 14 minutes, equal to about 14 litres, about 70% of the heat was absorbed by the water. The value of the first measurement varies strongly due to the switch of the water supply connections. This decreases the accuracy of the heat absorbed at the beginning. Besides, the time interval between measurements at the beginning was relatively large and sensible for mistakes. This makes the interpolation to calculate the area below the graph less reliable.

Moreover, a lot of measurements were strongly affected by the fins and therefore not usable. The placement tolerance of the thermocouples had a big influence on the position. If the thermocouples touched or came very close to a fin, the thermocouples measured an unexpected different temperature. This gave a distorted result of the temperature in the paraffin wax at the edge of the tube. Furthermore, the insulation of the setup was not optimal. This became very clear when the setup started to solidify, as the outside of the tube started to solidify first. The solidification further inwards was therefore not visible anymore. Better insulation ensures the losses to the environment would be limited and, therefore all the energy from the heat source was put in the paraffin wax instead of the surroundings. In addition, air bubbles in the paraffin wax arose during the heating and cooling of the setup thereby changing its local density and heat conductivity. Luckily it was easy to notice from the measurements when an air bubble arose near the thermocouples and it did not cause significant inaccuracies.

After all, the experimental work conducted was very purposeful and significant in relation to the research question. The experimental setup had its downsides but was sufficient to test the effect of the Spirotube on the heat transfer. With an optimized configuration, this could be increased further. All though the numerical model was very much simplified it did provide a good insight into the working principle of the heat battery. It was a simplified model of a potentially applicable model. The use of a third dimension and the addition of heat transfer over the tube would significantly contribute to this.

VI. Conclusion

This paper aimed to investigate whether a heat battery with a paraffin wax-based phase change material can be applied in a domestic application with the use of a fin structure.

The main problem of the use of paraffin wax as a PCM in a heat battery is its low thermal conductivity. Therefore, the storage of thermal energy in the paraffin wax takes a long time, as the heat is very slowly transported through the wax. From a theoretical point of view, the addition of a fin structure such as the one of the Spirotube was expected to speed up the process. The effect of the fin structure was, with a lot of assumptions and simplifications, illustrated in the numerical model. Where the release time of the model without the fin structure took more than 6 hours, the addition of the fin structure reduced this to about 17 minutes. The experiments showed that with the use of a Spirotube the release time was about 1 hour whereas with the regular copper tube it took more than 5 hours. A reduction in release time of more than 4 hours. The fins contribute to a significant increase in the heat flow, thus the heat battery stores and releases the thermal energy in a shorter time span. From the experimental results can be concluded that with 1,5 hour storage time and 1 hour release time, the heat battery does not meet the requirements to be applied in a domestic application in the researched configuration. The heat battery had to be able to release the stored heat within 15 minutes for a domestic application. Moreover, there is a lot more water with a constant temperature needed to melt and solidify all the paraffin wax than a small boiler contains. However, the measurements in figure 6 indicate that with the first 14 litres about 70% of the total heat was absorbed by the water due to the high heat flow in the beginning. This offers perspective for the use in a domestic application and with some improvements, the heat battery could potentially be suitable in a domestic application in the future.

VII. Recommendations

As discussed, the application of the Spirotube in a heat battery does not extract all of the heat within the requirements. However, about 70% of the heat could be extracted in the first 14 minutes. This offers perspective to further research optimization of the heat battery. The dimensions of the fins for example can be further researched to enhance the heat transfer. In addition, the heat stored and released into the paraffin wax was only measured as an indication, it would be interesting to measure this more precisely in the future to say something about the amount of heat that could be effectively stored and extracted from the wax. The experimental research showed that the fins were very dominant in the melting behavior. The chosen setup was not suited to measure the temperature at precise locations. This was done because in this research it was important to visually see what happened in the transparent tube. In future research other temperature measuring methods could be also taken into account. More research could be done on the local temperature over the length of the fin. In this report, every measurement was done with the same flow rate. The effect of a different flow rate on the melting process could also be examined. In terms of the numerical model, it was a simplified model of a potentially applicable model. Due to the complexity of the heat transfer over the length of the tube in combination with a lack of time, it was decided not to implement this addition to the model. It would result in poorly-founded research which would not have been useful. It is recommended to investigate this in further research and make use of the heat transfer over the length of the tube and the third dimension of the Spirotube which would result in a more reliable model. The complexity of the fin structure of the Spirotube remains difficult to model but could be modeled more detailed and realistically in future research.

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