

EXPERIMENTAL AND SIMULATIVE CHARACTERIZATION OF A FIN AND TUBES HEAT EXCHANGER WITH PCM FOR PROCESS HEAT APPLICATIONS

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Abstract

Thermal storage is one option to make solar or conventional process heat applications more efficient. Phase change material (PCM) storages offer the potential to keep constant temperatures for different time periods. In this paper a fin and tubes heat exchanger filled with the sugar alcohol D-mannitol was characterized regarding its usability as PCM storage in the temperature range between 100 and 250 °C. D-mannitol melts at ca. 166 °C. Different heating and cooling experiments were carried out. The specific heat capacity of the PCM as well as the latent heat was determined. The heat flow into the storage was determined at different mass flow rates for heating and cooling processes. During the measurements thermal losses to the ambient were very high leading to high uncertainties. Due to the viscosity of D-mannitol natural convection between the fins seems to have no significant influence on heat transfer during melting of the PCM. Some results led to the assumption that the heat distribution in the heat exchanger was not even. A simulation model was created and a first validation was carried out. Geometry improvement with the aim of more even heat distribution and higher charge and discharge power will be carried out by using the simulation model and further measurements.

Keywords: *Phase Change Material, D-mannitol, fin and tubes heat exchanger*

1. Introduction

Thermal storage offers the potential to increase energy efficiency of solar or conventional process heat applications. Thermal storage based on phase change materials (PCM) is advantageous for applications having to ensure small temperature differences during several hours. PCM can store high energy densities in small temperature ranges due to the phase change from solid to liquid. When storing above 100 °C PCM storages can be run unpressurised compared to water storages. In the temperature range between 100 and 250 °C sugar alcohols are potential candidates. They have higher storage densities than other materials in this temperature range.

In order to charge and discharge a PCM storage with sufficient power a suitable heat exchanger type has to be chosen. In a recent project a heat exchanger concept based on plates will be developed. As a reference for comparison an optimized fin and tubes heat exchanger with PCM will be used.

In this paper the characterization of the fin and tubes heat exchanger in combination with a sugar alcohol will be described. It was experimentally characterized in a testing facility. From the results first information about the behavior of the heat exchanger as well as about the PCM in application scale could be derived.

2. Experimental setup

Fig. 1, top left, shows a picture of the empty fin and tubes heat exchanger. Its inner dimensions are 270 x 259 x 81 mm. The distance between the fins is 4.5 mm with a fin thickness of 0.3 mm. The heat exchanger is made of stainless steel. Fig. 1, bottom left, shows the dimensions in cross section. The height of the fins is 28 mm. Under the fins is a gap of 26.5 mm. Thus when filling the heat exchanger with PCM, a 26.5 mm PCM layer will be under the fins. The temperature of the PCM is measured at the same height as the tubes, at three different locations in the heat exchanger (indicated in Fig.1, right). Additionally the temperature at the inner and outer surfaces of the insulation surrounding the heat exchanger is measured (the insulation is not visible in Fig. 1).

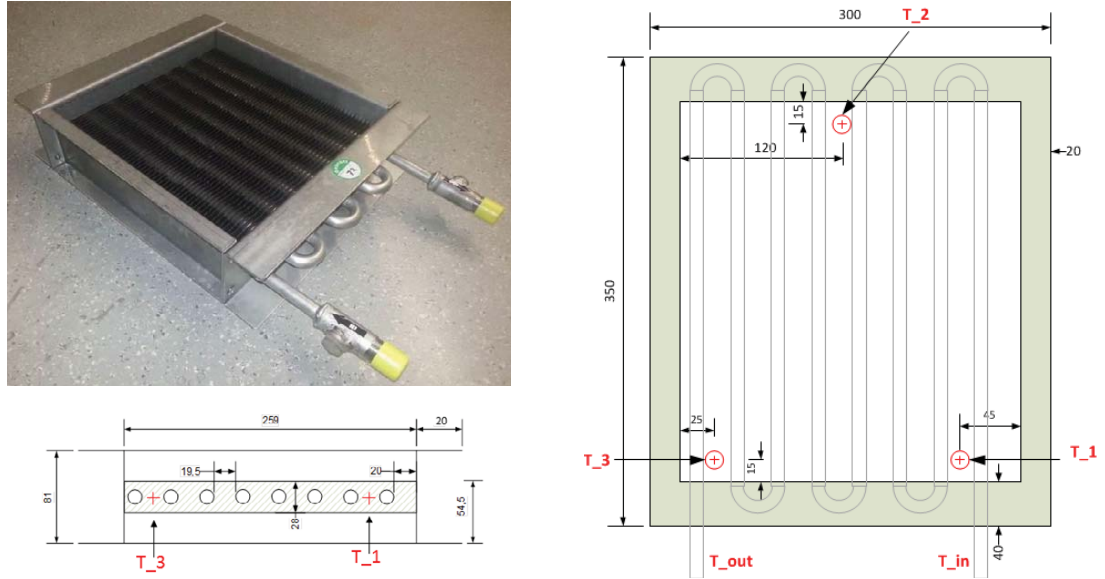


Fig. 1: Top left: fin and tubes heat exchanger used as PCM storage, bottom left: cross section of the heat exchanger with position of temperature sensors, right: position of temperature sensors from top view

In the testing facility thermal oil is used as heat transfer fluid (THERMINOL® 66 from FRAGOL GmbH+Co. KG). Mass flow is measured using a Coriolis mass flow meter. At the inlet and outlet of the heat exchanger the temperature of the oil is measured (Fig. 1, right).

The heat exchanger was filled with the sugar alcohol D-mannitol having a melting temperature of ca. 166 °C. Thermal properties of D-mannitol are presented in Tab. 1. The measurements not given a source were measured at Fraunhofer ISE.

Tab. 1: Thermal properties of D-mannitol

Property	Value solid	Value liquid	Material	Source
c_p (kJ kg ⁻¹ K ⁻¹)	1.79 (at 120 °C)	2.75 (at 180 °C)	Batch 1	
ρ (kg m ⁻³)	1390 (at 150 °C)	1267 (at 170 °C)		(Godin, 2015)
k (W m ⁻¹ K ⁻¹)	0.88 (at 130 °C)	0.43 (at 190 °C)	Batch 2	
η (Pa s)	-	0.046 (at 170 °C)	Batch 2	
β (1 K ⁻¹)		$1.3 \cdot 10^{-3}$		Based on (Godin, 2015)
Δh_m (kJ kg ⁻¹)	258.3 / 233.8		Batch 1 / Batch 2	
T_{onset} (°C)	160.9 / 150.4		Batch 1 / Batch 2	

3. Theory

To characterize the heat exchanger several properties were calculated.

The packing factor of the storage was calculated according to (Castell et al., 2011):

$$PF = \frac{V_{PCM}}{V_{storage}} \quad (\text{eq. 1})$$

Heat flow of the heat transfer fluid was calculated as:

$$\dot{Q}_{HTF} = \dot{m}_{HTF} * c_{p-HTF} * (T_{in} - T_{out}) \quad (\text{eq. 2})$$

The energy balance equation is written as:

$$\int_0^t \dot{Q}_{HTF} dt = \int_0^t \dot{Q}_{loss} dt + Q_{HX} + Q_{PCM} \quad (\text{eq. 3})$$

The energy of the insulation material was neglected.

With

$$Q_{HX} = m_{HX} * c_{pHX} * dT \quad (\text{eq. 4})$$

$$Q_{PCM} = m_{PCM} * c_{ps} * (T_{pc} - T_{start}) + m_{PCM} * \Delta h_{PCM} + m_{PCM} * c_{pl} * (T_{end} - T_{pc}) \quad (\text{eq. 5})$$

The UA-value was calculated as:

$$U * A = \frac{\dot{Q}_{HTF}}{\Delta T_{lm}} \quad (\text{eq. 6})$$

with the logarithmic mean temperature difference for a PCM storage according to (Mehling and Cabeza, 2008):

$$\Delta T_{lm} = \frac{(T_{pc} - T_{in}) - (T_{pc} - T_{out})}{\ln \frac{T_{pc} - T_{in}}{T_{pc} - T_{out}}} \quad (\text{eq. 7})$$

The effectiveness was calculated according to (Castell et al., 2011) as follows:

$$\varepsilon = \frac{T_{in} - T_{out}}{T_{in} - T_{pc}} \quad (\text{eq. 8})$$

The PCM temperature was assumed to be a mean value of the three measured temperatures in the PCM:

$$T_{pc} = \frac{(T_1 + T_2 + T_3)}{3} \quad (\text{eq. 9})$$

4. Experiments

In the beginning measurements with the empty heat exchanger were carried out. Thermal losses to the ambient were determined at different temperatures and mass flow rates. Before starting the measurements the temperature was kept constant until steady state was reached. During the measurements a constant inlet temperature T_{in} was supplied for half an hour. \dot{Q}_{loss} was calculated using (eq. 2). Afterwards the specific heat capacity of the empty heat exchanger was determined. Therefor a step function was implemented to the inlet temperature T_{in} . Calculation was done with (eq. 3) and (eq. 4). In (eq. 3) Q_{loss} was calculated from the determined losses in the measurement before and Q_{PCM} was zero. The results of these experiments were needed to calculate further values of the heat exchanger filled with PCM.

Afterwards the heat exchanger was filled with D-mannitol. The material was filled until the upper end of the fins. Thus a gap of air was left to tolerate the volume change of the PCM. D-mannitol was filled into the heat exchanger in fresh form, thus as a powder. Once the powder was filled until the upper end of the fins, it was heated over the phase change and cooled down again. Thus it melted and crystallized once. After crystallizing, the D-mannitol was a solid mass. Since the density of D-mannitol in this state is much higher than the one of the powder, five of these filling, melting and crystallization processes were necessary. During these processes coloration to brown started which is a hint for degradation (Solé et al., 2014).

After finishing most experiments a second filling process was done, because some experiments (heating and cooling through the phase change) were repeated using fresh material. For this filling process the D-mannitol was melted in an oven and afterwards poured into the heat exchanger in liquid state. Thus only one melting cycle was necessary leading to less degradation during the filling process.

In all experiments with D-mannitol a step function was implemented to the fluid inlet temperature T_{in} at constant mass flow. Before starting an experiment the oil inlet temperature was kept constant for several hours to reach steady state. First, experiments in sensible state of the PCM were carried out (in solid and in liquid state) in order to determine the specific heat capacity of the PCM in solid and liquid state. The calculation of the specific heat capacity was done using (eq. 3) and (eq. 4). Afterwards measurements including the phase change were carried out. Several step functions for heating and cooling at different mass flow rates were performed and analyzed. The latent heat, the UA-value, the effectiveness and the heat flow were calculated for this case using (eq. 2) to (eq. 9).

5. Results and discussion of experiments

5.1 Packing factor

In total 4.29 kg of D-mannitol were implemented into the heat exchanger during the first filling. As described, some experiments were repeated using fresh material and a different filling procedure. Using this procedure the heat exchanger was filled with 5.1 kg of D-mannitol. The filling level after the second procedure was a bit higher than after the first one. The PCM contents lead to packing factors according to (eq. 1) of 0.55 after the first filling and 0.61 after the second filling taking into account the inner dimensions of the heat exchanger (and thus the air gap). The packing factor of this heat exchanger mainly depends on the dimensioning of the air gap on top of the fins and the PCM layer under the fins.

5.2 Thermal losses

Fig. 2 shows the results of the thermal losses to the ambient measured in empty state of the heat exchanger. They increase with increasing oil inlet temperature T_{in} . The relative standard uncertainty of the thermal losses is quite high (up to 25 %). The reason for that is the small temperature difference between oil inlet and outlet temperature.

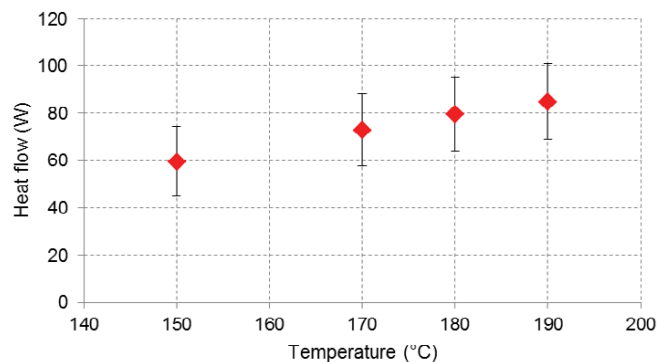


Fig. 2: Thermal losses of the heat exchanger through the insulation material at a mass flow rate of 5.5 kg/min and different oil inlet temperatures T_{in}

5.3 Natural convection

In liquid state of the PCM natural convection can occur. This heat exchanger has two different regions of PCM: the region between the fins and the PCM layer under the fins (see Fig. 1). The Rayleigh number for the region between the fins was calculated according to (Deborah A. Kaminski, Michael K. Jensen, 2011) (natural convection in vertical enclosures). The exact value of the Rayleigh number depends on the material property data. The expansion coefficient β was calculated based on density literature data and its uncertainty is not clear until now. A lower expansion coefficient would lead to a lower Rayleigh number. According to (Deborah A. Kaminski, Michael K. Jensen, 2011) viscous forces are much larger than buoyancy forces and no fluid motion occurs if the Rayleigh number is lower than 2000. Fig. 3 shows the calculated Rayleigh numbers depending on the fin distance and for three temperature differences between liquid PCM and wall. Assuming a temperature difference of 5 K, the Rayleigh number reaches 2000 at a fin distance higher than 5 mm. For a temperature difference of 10 K the value is reached slightly above 4 mm. Taking into account a temperature difference of 15 K, it is reached at approximately 3.6 mm.

It is assumed that natural convection will start developing slowly at Rayleigh numbers higher than 2000. In completely liquid state natural convection between the fins might occur very weakly in the present heat exchanger at temperature differences between PCM and fin higher than 10 K. During the melting process it is assumed that natural convection between the fins has no significant influence on the heat transfer of the heat exchanger. During melting the gap between the melted and the still solid PCM will grow. Until a liquid layer of 3.6 to 4 mm is reached, no natural convection will occur. After that, it might occur very weakly, but as the gap is only 4.5 mm width, most of the melting process has already happened without natural convection.

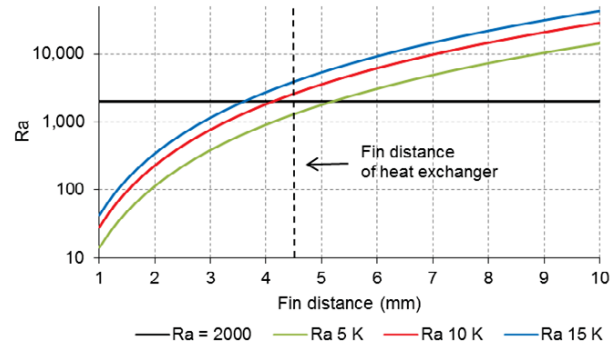


Fig. 3: Raleigh number of D-mannitol in a vertical enclosure according to (Deborah A. Kaminski, Michael K. Jensen, 2011)

In the PCM layer under the fins natural convection should occur when the PCM is completely in liquid state. Heating and cooling of the PCM layer takes place from the top. So during cooling convection in this region should be developed more intense than during heating.

5.4 Temperature profiles and temperature distribution in the PCM

Fig. 4 shows two examples of the step functions carried out in the sensible state of the PCM, the left one in solid and the right one in liquid state. Oil inlet and outlet temperature as well as the three PCM temperatures are shown. At the time the measurements were stopped the PCM had not reached the oil temperature. In solid state the PCM temperatures come closer to the oil temperature after 60 min than in liquid state. This is due to the higher heat conductivity of the solid PCM compared to the liquid PCM. As the PCM temperatures are measured between the fins and the temperature difference between the oil and the PCM is lower than 5 K after 60 min no natural convection occurs. Thus heat conductivity is the dominant factor for heat transfer in this case.

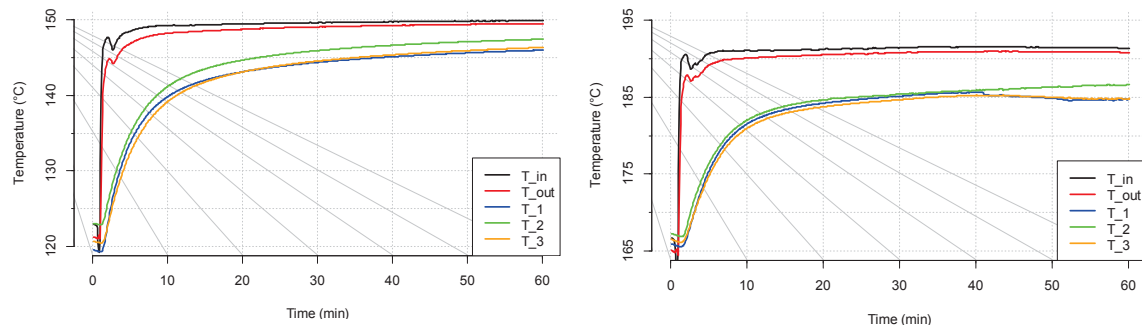


Fig. 4: Left: step function in solid state of the PCM (mass flow = 5.8 kg min^{-1})
right: step function in liquid state of the PCM (mass flow = 6 kg min^{-1})

Fig. 5 shows one melting (left) and one crystallization cycle (right) of the PCM in the heat exchanger. The inlet and outlet temperature of the oil as well as the PCM temperature is shown. Melting takes place at ca. $165 \text{ }^\circ\text{C}$ whereas the crystallization plateau is visible at $162.5 \text{ }^\circ\text{C}$, thus a hysteresis of 2.5 K is visible. Additionally supercooling takes place during crystallization. DSC-measurements of D-mannitol showed hysteresis of up to 40 K (Solé et al., 2014). The much lower hysteresis in the heat exchanger can have several reasons: I) it could be due to the higher sample mass. II) If not all the PCM was melted in the heating cycle before, the still solid PCM could have acted as nucleus. III) The surface of the heat exchanger could also have acted as nucleus. This will be examined in future work.

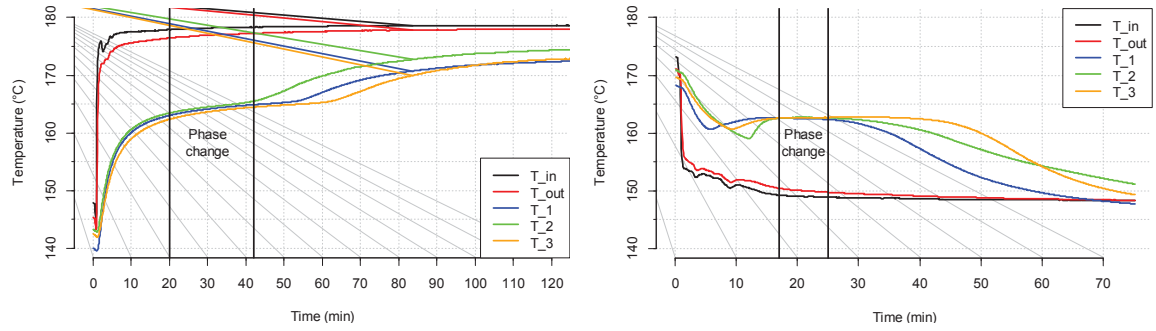


Fig. 5: Left: melting of the PCM; right: crystallization of the PCM both at a mass flow rate of 5.5 kg min^{-1}

Fig. 6 shows one measurement during the phase change. In this case the temperature sensors in the PCM were put deeper into the PCM close to the bottom plate of the heat exchanger. At the end of the measurement the PCM temperatures reach $170 \text{ }^\circ\text{C}$, which is slightly above the melting temperature or could still be at the upper end of the melting range. Nevertheless the PCM temperature does not show a visible melting plateau. So it cannot be assured that the PCM at all locations of the heat exchanger was melted completely. The other measurements during the phase change were stopped after 180 min. Thus in these measurements it cannot be assured that all the PCM in the heat exchanger was melted, especially in the ones with lower temperature differences between oil inlet temperature and PCM temperature.

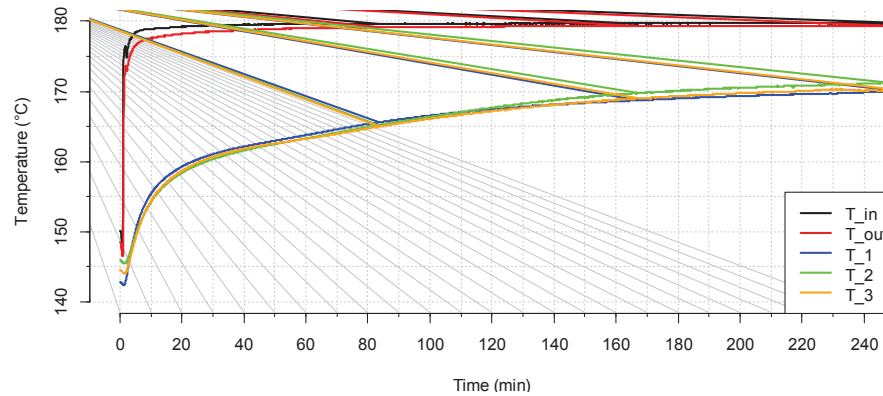


Fig. 6: Melting of the PCM with temperature sensors close to the bottom plate at 8 kg min^{-1}

At the right margin of the heat exchanger the distance between tube and margin is higher than the distance between the tubes in the other parts of the heat exchanger (see Fig. 1, right). After having finished all measurements and opened the heat exchanger, it was visible that the PCM in this part was less brown than the rest of the PCM surface, which might be an indication for less degradation. This effect might have been caused by lower temperatures occurring in this part or by melting this PCM less often than the PCM in the other locations. The darkest brown parts visible in Fig. 7 are on top of the tubes. It could be an indication that the PCM above the tubes was exposed to the highest temperatures.

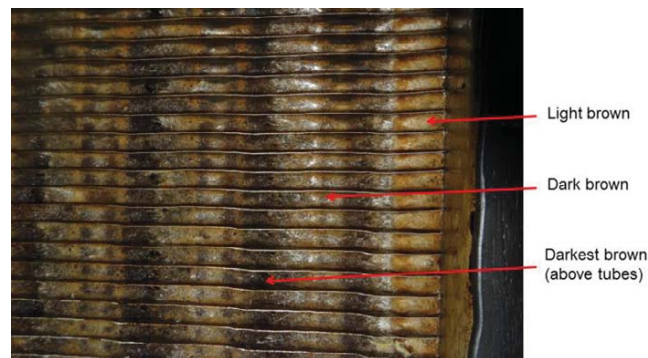


Fig. 7: Surface of the D-mannitol in the heat exchanger after having finished the experiments. The surface close to the right margin is lighter brown than the rest of the surface. The material above to the tubes shows the darkest brown coloration.

5.5 Determination of specific heat capacity and latent heat

Tab. 2 shows a summary of the calculated specific heat capacity and latent heat. Given values are mean values of several measurements. A comparison of the obtained c_p -value for the empty heat exchanger with literature data shows good accuracy.

Tab. 2: Summary of determination of specific heat capacity and latent heat

Measurement	Result (mean value)	Comparative DSC-measurement respectively literature value
c_p HX (empty) ($\text{kJ kg}^{-1} \text{K}^{-1}$)	0.55 +/- 11.3 % (at 152.6 °C)	0.518 (at 150°C) (Richter)
c_p D-mannitol solid ($\text{kJ kg}^{-1} \text{K}^{-1}$)	1.65 +/- 33.3 % (at 134.2 °C)	1.79 +/- 5 % (at 120 °C)
c_p D-mannitol liquid ($\text{kJ kg}^{-1} \text{K}^{-1}$)	2.86 +/- 28.5 % (at 175.9 °C)	2.75 +/- 5 % (at 180 °C)
Δh_m (kJ kg^{-1})		
1 st filling	142.8	Fresh material: 258.3 After measurements in HX: 200.0
2 nd filling	179.5	Fresh material: 233.8 After measurements in HX: 219.3

Comparing the specific heat capacity of D-mannitol in solid and liquid state to DSC-measurements, it is visible that the value of the solid state is lower than DSC and the one of liquid state is higher than the DSC measurement. Both heat exchanger measurements were stopped after 1 h (see Fig. 5). It is assumed that no homogeneous temperature distribution in the PCM was reached as the lower PCM layer is not well thermally coupled to the rest of the heat exchanger. This leads to an underestimation of the specific heat capacity. In liquid state heat transfer in the PCM layer under the fins might take place faster due to convection in this part. The high standard uncertainty of the thermal losses (see Fig. 2), that are taken into account in the calculation of the specific heat capacity, additionally lead to a deviation between the measurements in the heat exchanger and in the DSC.

The standard uncertainty of the specific heat capacity of the empty heat exchanger is lower than the one of the specific heat capacity of the PCM in solid and liquid state. The reason is the shorter measurements time of ten minutes in case of the measurement of the empty heat exchanger compared to 1 h in the other two cases. When considering energy balances, the uncertainty increases with increasing measurement time due to the uncertainty of the losses to the ambient (see Fig. 2).

The comparison of the latent heat with DSC-measurements shows differences. DSC-measurements of the PCM were carried out before filling the heat exchanger and after finishing all measurements. A decrease from 258.3 to 200.0 kJ kg^{-1} takes place. This is due to the degradation of D-mannitol under oxygen atmosphere (Solé et al., 2014). The calculation of the latent heat based on the heat exchanger measurements gives a value of 142.8 kJ kg^{-1} and thus almost 60 kJ kg^{-1} lower than the DSC-measurement after the treatment in the heat exchanger. Due to the geometry of the heat exchanger it could not be ensured that the PCM below the fins was melted completely (see Fig. 6). In the calculations the mass of the whole PCM is taken into account instead of only the molten part, which leads to an underestimation of the latent heat. A further reason for the difference between the measurements in the DSC and in the heat exchanger is the standard uncertainty of the heat losses to the ambient of the heat exchanger of up to +/- 16 W (see Fig. 2). Due to the long measurement time to determine latent heat of up to 3 h, the high standard uncertainty of the heat losses lead to an even higher standard uncertainty of latent heat. When calculating the latent heat with heat losses that are 16 W lower, a latent heat of approximately 180 kJ kg^{-1} is calculated. After the second filling the difference is a bit lower. In this case the temperature difference between inlet temperature and melting temperature was higher. So it might be possible that more PCM was melted.

5.6 Characterization of the phase change period

To be able to compare the performance of the investigated heat exchanger to the performance of other heat exchangers, some characteristic parameters were calculated. As the heat exchanger is used to melt or crystallize the PCM inside the storage, the parameters were calculated for these phase transitions (marked in Fig. 5). Afterwards a mean value over the phase change period was calculated to compare different measurements to each other.

Fig. 8 (left) shows the mean value of the heat flow of the heat transfer fluid during the phase change (absolute value). The logarithmic mean temperature difference between PCM and heat transfer fluid (see Fig. 8, right) was almost the same in all measurements, but in the case of crystallization with the mass flow of 1.8 kg min⁻¹ it was lower than during melting.

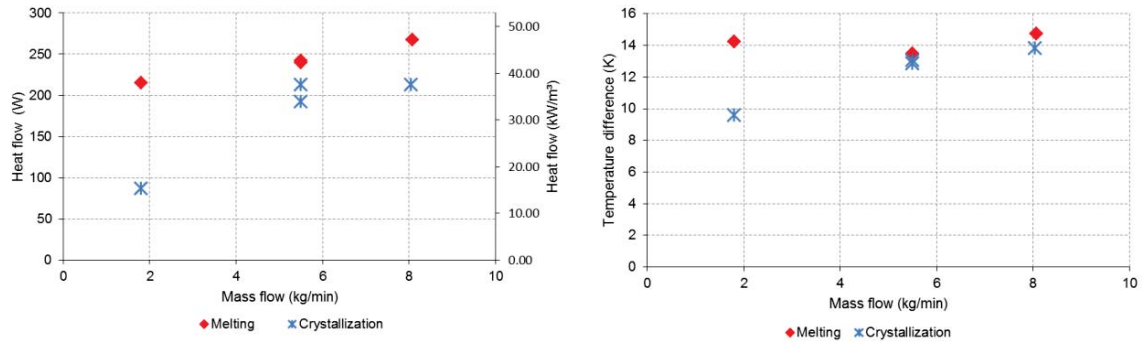


Fig. 8: Left: mean value of the heat flow (\dot{Q}_{HTF}) during the phase change (absolute value), right: mean value of the logarithmic mean temperature difference between PCM and heat transfer fluid during the phase change

To make the obtained heat flows comparable to each other, the UA-value of the heat exchanger was calculated taking the heat flow and the logarithmic mean temperature difference of Fig. 8 into account. Fig. 9 shows the results.

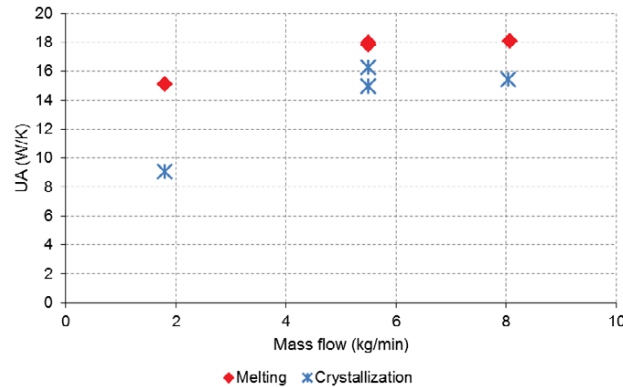


Fig. 9: UA-value at different mass flow rates

According to the results the UA-value is higher during melting than during crystallization. This result has to be interpreted carefully, because many uncertainties due to the way of calculating the UA-value appear. For calculating the UA-value of the heat exchanger properly, it would be necessary to consider only the heat flow between the heat transfer fluid and the PCM. The calculation for Fig. 9 was done using the heat flow of the heat transfer fluid (\dot{Q}_{HTF}) according to (eq. 2). This heat is not completely transferred to the PCM. During charging part of it goes to the storage enclosure and from there to the ambient and to the colder PCM. Thus the UA-value is overestimated. During discharging, not only the heat of the PCM is transferred to the heat transfer fluid, but also heat from the storage envelope. Part of the heat from the envelope and most likely from the PCM also goes to the ambient. Thus for discharging it cannot be judged if the UA-value is under- or overestimated without further investigation. In order to evaluate the UA-value properly further measurements and calculations have to be carried out to determine only the heat transfer between the heat transfer fluid and the PCM.

A further uncertainty is the calculation of the logarithmic mean temperature difference. The phase change temperature T_{pc} was calculated as a mean value of the three temperature sensors inside the PCM. As all of them are installed between the fins, the temperature regarded as PCM temperature might not be representative for the whole PCM. The phase change might take place at different times in different parts of the PCM.

Fig. 10 shows the effectiveness of the heat exchanger. It increases with decreasing mass flow. In case of the mass flow rate of 1.8 kg min⁻¹ the effectiveness during crystallization is lower than during melting. The reason is the smaller logarithmic mean temperature difference during crystallization compared to melting (see Fig. 8, right). The effectiveness of this heat exchanger is low compared to other PCM-storages. (Castell et al., 2011) reach more than 50 % in a tube in PCM tank. One reason could be that the PCM layer under the fins is not

activated properly. Additionally the mass flow could be further reduced to increase the effectiveness.

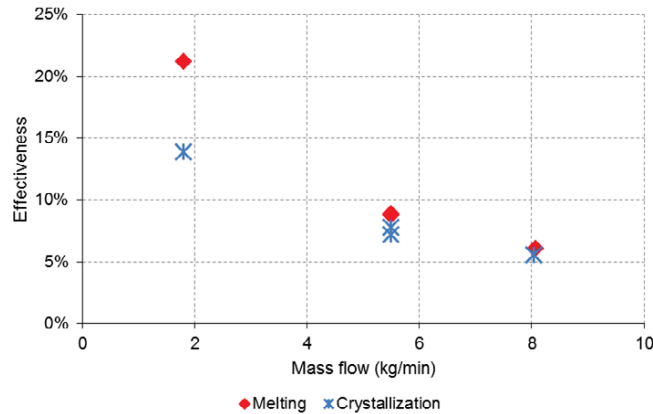


Fig. 10: Mean value of the effectiveness during the phase change

6. Model validation and simulation

A simulation model for the fin and tubes heat exchanger was created in COMSOL Multiphysics. A first model validation was carried out for one heating and one cooling cycle. Material properties of D-mannitol were chosen according to Tab. 1. Latent heat of the PCM was introduced to the model based on measured data from the DSC. Natural convection in liquid part of the PCM was not taken into account (neither between the fins nor in the PCM layer under the fins). The envelope and the insulation of the heat exchanger were not taken into account. Losses to the ambient were introduced as constant heat flow with values taken from the measurements according to Fig. 2. A comparison of the oil as well as PCM temperatures for the heating and the cooling case are shown in Fig. 11.

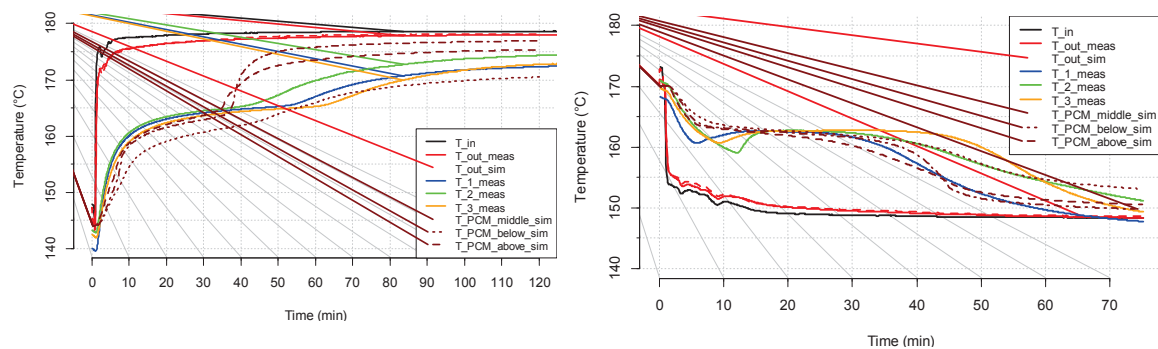


Fig. 11: Validation of the simulation model at a mass flow rate of 5.5 kg min^{-1} : comparison of simulated and measured temperatures for heating (left) and cooling (right)

The highest differences are visible in the PCM temperatures. One uncertainty is the latent heat of the D-mannitol due to its degradation. Measurements of the latent heat were carried out with the fresh material and after having finished all experiments. This experiment taking for validation was done at some time in between the two DSC measurements. Thus the value for the latent heat of the fresh material will be too high and the one of the degraded PCM will be too low. The DSC data taken is the one of the fresh material, thus latent heat in this simulation might be overestimated. The simulation shows that the height of the locations where temperature is measured is important. In the measurements it cannot be assured if the PCM temperature was measured exactly at a height in the middle of the tubes. The simulation shows that moving the temperature sensor 1 cm up or down can lead to temperature differences of up to 5 K.

In the cooling case the melting temperature of the PCM was shifted downwards 2.5 K. The nucleation is not modeled. Still the PCM temperatures seem to fit better to the measurement during cooling than during heating.

Although there are still uncertainties in model validation, the model reproduces the main characteristic of the fin and tubes heat exchanger with D-mannitol. That is why the model was already used to compare the heating and cooling process under similar circumstances to each other.

The same model used for validation was used in a simulation, but this time no losses to the ambient were introduced. Thus all the heat from the heat transfer fluid was transferred via the heat exchanger to the PCM. The envelope was not taken into account in this simulation. Fig. 12 shows the results of the UA-value. Here the result during crystallization is higher than during melting. As natural convection was not taken into account, thermal conductivity is crucial for the heat transfer. During melting it is the thermal conductivity in liquid PCM, during crystallization it is the one in solid state. Thermal conductivity in solid state is two times higher than the one in liquid state. This characteristic could not be shown in the measurements until now due to the above described reasons. Thus, the model helps to analyze the heat transfer processes in the heat exchanger in more detail and will be used for further analysis and optimization.

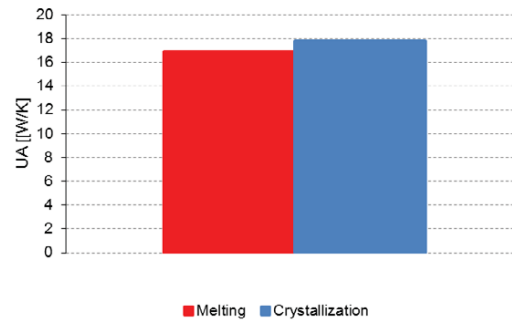


Fig. 12: Comparison of UA-value during melting and crystallization from a simulation without thermal losses to the ambient

7. Conclusion and outlook

A fin and tubes heat exchanger with D-mannitol was experimentally characterized. A simulation model was created and a first validation was carried out.

During experimental characterization the thermal losses to the ambient were very high in relation to the heat transfer of the heat exchanger itself. To reduce the losses and make the boundary conditions of different measurements more comparable a heating device will be installed around the heat exchanger in future. Thus ambient temperature will be raised and thermal losses reduced.

More temperature sensors will be installed in future experiments to determine the heat transfer more exactly. Inside the PCM more sensors are needed to determine temperature differences in the PCM as seen in the simulation. Especially differences in the height of the PCM are expected.

The strong degradation of D-mannitol in oxygen atmosphere leads to uncertainties during evaluation of the experiments and model validation. To reduce the degradation of D-mannitol the experiments should be carried out under controlled atmosphere. Alternatively a different PCM with a melting temperature between 100 and 250 °C that does not show degradation should be used.

When using D-mannitol as PCM a larger fin distance than 5 mm seems to be reasonable to increase charging power by the influence of natural convection. How much natural convection influences charging power at higher fin distance shall be examined by further tests and simulation. In general, the effect of different fin distances for charging and discharging process shall be tested by using the simulation model and further measurements.

The simulation model has to be improved. The envelope and the insulation will be taken into account to reduce deviations to the measurements. Additionally natural convection will be implemented in order to determine its effect also with the help of the simulation model. By improving the measurements with the means stated above, it will be possible to carry out the model validation with more accuracy.

To increase the thermal power of the PCM heat exchanger it might be reasonable to fabricate it out of a material with higher heat conductivity than stainless steel, e.g. aluminum. To ensure that the whole PCM will be melted or crystallized in convenient time, the layer of PCM below the fins should be reduced, thus the fins should reach the bottom plate of the heat exchanger. Further geometry parameters as fin thickness, piping and outer dimensions will be optimized by the help of the simulation model.

8. Acknowledgment

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9. References

- Castell, A., Belusko, M., Bruno, F., Cabeza, L.F., 2011. Maximisation of heat transfer in a coil in tank PCM cold storage system. *Applied Energy* 88 (11), 4120–4127.
- Deborah A. Kaminski, Michael K. Jensen, 2011. Convection Heat Transfer. Chapter 12, in: Deborah A. Kaminski, Michael K. Jensen (Ed.), *Introduction to Thermal and Fluids Engineering*, Updated Edition.
- Godin, A., 2015. Sugar alcohols properties and performances. FP7 project - SAM.SSA, Workshop and Onsite Demonstration, 03/2015, Bilbao.
http://samssa.eu/fileadmin/samssa/downloads/workshop/presentations/Session-1_Alexandre-Godin_Sugar_alcohols_properties_and_performances.pdf. Accessed 26 September 2016.
- Mehling, H., Cabeza, L.F., 2008. Heat and cold storage with PCM. An up to date introduction into basics and applications. Springer, Berlin Heidelberg.
- Richter, F. Die physikalischen Eigenschaften der Stähle "Das 100-Stähle-Programm". Teil I: Tafeln und Bilder, Mülheim a. d. Ruhr.
https://www.tugraz.at/fileadmin/user_upload/Institute/IEP/Thermophysics_Group/Files/Staehle-Richter.pdf. Accessed 20.7.16.
- Solé, A., Neumann, H., Niedermaier, S., Martorell, I., Schossig, P., Cabeza, L.F., 2014. Stability of sugar alcohols as PCM for thermal energy storage. *Solar Energy Materials and Solar Cells* 126, 125–134.