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Separation of power and capacity in latent heat energy storage

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Abstract

The state-of-the-art latent heat energy storage system is equipped with aluminum fins at the heat exchanger pipes in order to compensate the low thermal conductivity of the phase change material (PCM). The necessary amount of fins is directly coupled to the capacity of the storage system, what makes larger systems expensive. The PCMflux concept is developed in order to realize both a controllable and a possibly more cost effective latent heat storage system. These aims are addressed by separating the storage material from the heat exchanger. As a result, the PCM can be moved over the heat exchanger. The PCM thereby is macroencapsulated into containers. These pass the heat exchanger while the PCM inside changes phase. In order to improve thermal contact between containers and heat exchanger, Hitec® as an intermediate fluid is used to avoid poor dry contact. In this article, an experimental setup is described to examine the heat transfer through thin layers of molten Hitec®. The results of the experiments show an increased heat transfer by a factor of 9.9. This improves feasibility of the PCMflux concept significantly.

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Keywords:Latent heat storage; Phase Change Materials;Separation of power and capacity;Heat transfer through fluid layer;Moving PCM

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1. Introduction

With a growing share of fluctuating renewables in the energy mix, energy storage technologies gain increasingly importance. In combination with solar thermal power plants, thermal energy storage can contribute effectively to a stable and green electricity production. Due to the possibility to employ thermal energy storage, this kind of power

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plant can smooth out the production and demand curve of electricity. In case of direct steam generating solar thermal power plants, an effective way to store heat is to make use of latent heat storage. This kind of technology utilizes the phase change of storage materials, e.g. salt nitrates. In the physical process of phase change, the heat of fusion of the involved material is used to store heat. The phase change occurs at a constant temperature, so does the water-steam system within the heat exchanger of the power plant. Choosing the phase change material (PCM) according to a melting temperature close to the phase change temperature of the water-steam system, a huge amount of heat can be stored within a very small temperature difference ΔT. Due to the small occurring ΔT between the water-steam system acting as the heat transfer fluid (HTF) and the storage material over the whole operating time, the exergy losses can be minimized. This promises good overall efficiencies. The state-of-the-art latent heat storage shows a characteristic heat flux drop over time while discharging the storage [1,2]. This is a conceptual problem induced by the growing layer of frozen PCM in areas with highest heat transfer close to the heat exchanger pipes. In this layer, convection effects are suppressed and the poor thermal conductivity of the storage material comes severely into effect. The resulting decrease of heat flux can be damped by the employment of fins into the PCM. Here, the fins fill the whole storage volume. That is why the number of necessary fins is dependent on the storage capacity. This makes the system expensive. Additionally it still shows the drop of heat flux, even though it is less distinct. The PCMflux concept follows a different way to overcome the heat flux drop while discharging. The concept is based on the separation of power and capacity, meaning that the heat exchanger no longer has to be adjusted to the storage`s size. It needs to be designed for the necessary power of the storage unit, only. This is realized by moving storage material. The resulting thermal power thereby can be controlled via the forward velocity of the storage material. The PCM is encapsulated into containers. These are moved over the heat exchanger. To improve thermal contact between heat exchanger and enclosed storage material, a fluid layer consisting of Hitec® is employed to avoid dry contact between these components. The following chapters deal with a brief description of the PCMflux concept and the experimental examination of the heat transfer through molten Hitec® fluid layers of different heights. The PCMflux concept is developed within the framework of the “nextPCM” project. While DLR focusses here on the PCMflux technology, Novatec Solar GmbH works on the aspects related to the integration of PCM storage technology into concentrated solar power plants (CSP). Aim of the initial experimental study described in this paper is to ascertain, if the implementation of the above mentioned fluid layer into the PCMflux concept comes with significant improvements of heat transfer.

2. Role of the fluid layer within the PCMflux concept

Separating the power of a latent heat storage system from its capacity, the storage material needs to be decoupled from the heat exchanger. For that reason, the PCM is encapsulated into containers, which are used to transport the storage material. If these containers are moved with a specific forward velocity while passing the heat exchanger, a quasi-stationary phase change interface is established inside the containers. As soon as this state is realized, the storage system shows a constant heat flux over time and the characteristic heat flux drop of state-of-the-art latent heat storage systems is avoided. The crystalized layer of PCM close to the heat exchanger doesn`t grow over time in this case. This is because the storage material, that changed phase recently, is transported away steadily. As a result, the PCMflux concept shows a nearly constant thermal resistant between storage material and heat exchanger leading to a nearly constant heat flux over the whole time of operation. The forward velocity of the storage material thereby directly influences the heat flux of the PCMflux system. Within a design specific range of velocity, the heat flux can be controlled accurately. Details of that system together with the detailed theoretical background of the PCMflux system can be found in references [3,4].

There are principally two designs of the PCMflux system possible, see Fig. 1 and Fig. 2. Regarding the alignment of the heat exchanger pipes, the different designs are separated into a vertical and a horizontal version. In the vertical concept, see Fig. 1, the heat exchanger pipes can be used from both sides for heat transfer. On the other hand, the containers have to be designed very flat. This enlarges the danger of buckling. The density of PCMs usually differs from liquid to solid state. This causes tensions inside the containers while the storage material is changing phase. This possibly leads to buckling of the containers. In the vertical concept, the containers must not alter their shape. If they would, they would jam between the modules and therewith brake down the system. This would have to be avoided with thick container walls. But this again would make the system expensive. Contrary, the horizontal version promises to solve the tension problem differently, see Fig. 2.

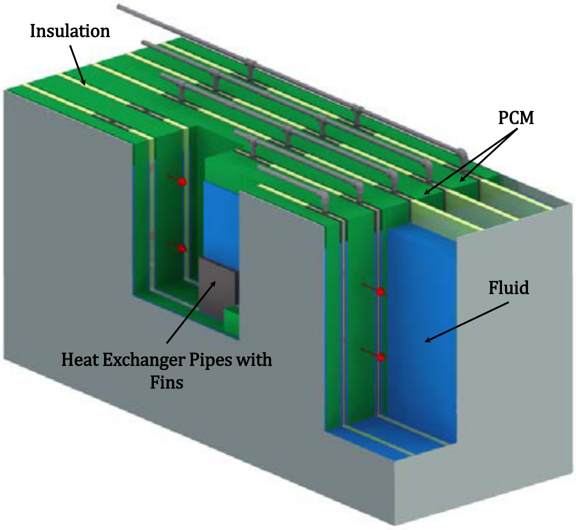

Fig. 1. Vertical PCMflux design

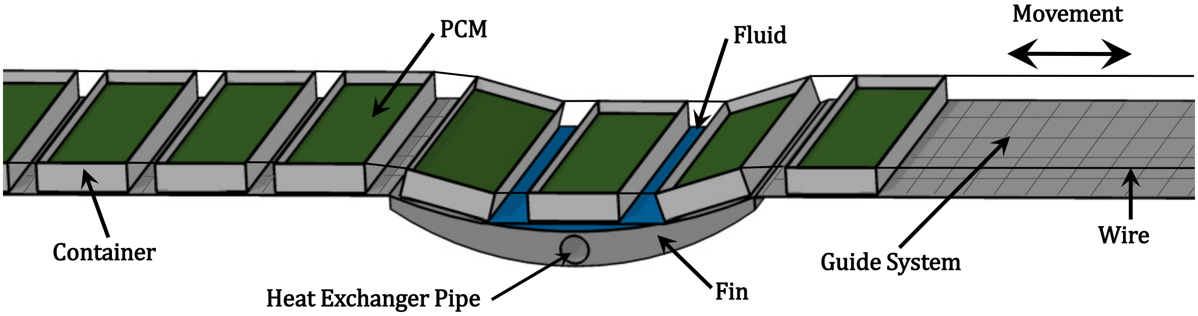

Fig. 2. Horizontal PCMflux design

The stress on the containment caused by the density alteration while undergoing the phase change of the storage material is supposed to be reduced by employment of open containers in the horizontal version. For example: $NaNO_3$ shows in the liquid and solid phase a density of 1900 kg/m^3 and 2260 kg/m^3, respectively [5]. High and flat containers as necessary in the vertical design need to be thick-walled in order to withstand the tensions. This makes them material intensive. Less material is needed in the horizontal design, in which open and plain containers made of thin aluminum foil can be employed. The tensions are supposed to be released by the opening of the containers. These boxes are filled with PCM and connected to each other by wires, see Fig. 2. The whole weight of the containers is carried by a guide system consisting of cost effective material. This guide system is interrupted by a heat exchanger connected to the heat exchanger pipe. The containers are moved by pulling the wires into the claimed direction. As soon as they reach the heat exchanger, they sink into the slightly bent heat exchanger until they touch its surface. While passing the heat exchanger, the storage material changes phase until the containers reach the other side of the heat exchanger. After a complete phase change, the containers are reattached to the guide system beyond the heat exchanger. For discharging the storage, the containers are moved into the other direction. The shape of the heat exchanger is influenced by the usage of the fluid layer, see Fig. 2. It is bowl like shaped in order to keep the fluid layer inside the heat exchanger while the containers are transported through it. The thin fluid layer is foreseen to improve heat transfer due to avoiding dry contact between container and heat exchanger bowl by replacing isolating air with fluid in their contact area. This layer consists of Hitec® due to following reasons: It can stand the occurring high temperatures up to 538°C [6]. And – compared to liquid metals – it is a cost effective material [7]. Nevertheless, Hitec® shows a poor thermal conductivity like most nitrate based molten salts. To minimize its own thermal resistance, the fluid layer has to be as thin as possible. This is ensured by seating the containers directly on the heat exchanger. Since the melting point of this eutectic mixture is between 140°C and 142°C [6,7], it is much lower than the melting temperature of the employed storage material inside the containers. Therefore, it stays liquid all the operational time, although the storage material is cycled. In the experimental setup described in the next chapter, the eutectic mixture of $NaNO_3$ (46wt%) and KNO_3 (54wt%) is used as storage material with a melting temperature of 222°C [8].

2.1. Theoretical background

Contacting different materials or different components mechanically usually comes with a thermal resistance in the contact area due to small surface irregularities. There are some peaks, that are directly in contact with each other and some gaps filled with the contact area surrounding medium, see Fig. 3 (a) and (b). Heat can pass either directly over the peaks or has to pass the gaps filled with surrounding medium [9].

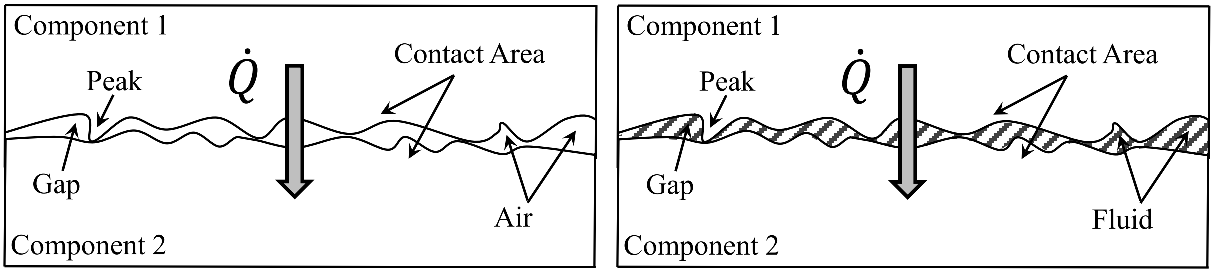

Fig. 3. Contact area of two components with surface irregularities with resulting peaks and gaps filled with (a) air; (b) fluid

The separation of the storage material from the heat exchanger within the PCMflux concept via many containers leads to huge contact areas between PCM containers and heat exchanger. Due to manufacturing and economic reasons, no specially treated materials, e.g. materials with polished surfaces, shall be employed in the system. That is why one critical issue for the PCMflux concept is the heat transfer from the storage material to the HTF and vice versa. If these contact areas caused a too high thermal resistance, the losses at the contact areas would lead to a low temperature difference from the HTF to the melting temperature of the PCM. This would result in a low heat flux. In case of dry contact, the gaps are filled with air. And air has a very low thermal conductivity ($\lambda_{Air} = 0.04\, W/mK$ at $222°C$ [10]) leading to high thermal resistances in the contact areas. One idea of the PCMflux concept is to reduce the thermal resistance by replacing the air with a fluid (Hitec®) that has a better thermal conductivity ($\lambda_F = 0.49\ W/mK$ at $222\ °C$ [11]) than air, see Fig. 3 (b). This is supposed to improve thermal contact between the heat exchanger and the containments of the storage material while they are moved. Additionally, not only direct contact is examined, but also different heights of the fluid layer. This could be the case within the PCMflux system, if buckling of the PCM containers could not be avoided completely. If there are areas of longer distances between containers and heat exchanger, the resulting thermal resistance has to be known. Depending on that resistance, the effort on avoiding the container buckling, e.g. by the implementation of thicker container walls, can be valued.

In the experiments described in this paper, an integral value for the thermal resistance including the contact resistance and the resistance due to the height of the fluid layer H_F is calculated. This is conducted via equation (1):

$$R_{th} = \frac{\Delta T_F}{\dot{Q}} \tag{1}$$

In equation (1), R_{th} signifies the thermal resistance, $\Delta \mathrm{T}_F$ the temperature drop over the fluid layer measured by the difference $T_1 - T_2$ and $\dot{Q}$ for the heat flow passing the bridge between HTF and PCM, see Fig. 4 (a) and (b). This heat flow is calculated via the temperature difference $\Delta T_{\dot{Q}}$ measured by the two measuring points inside the bridge, the cross sectional area of this bridge A, the distance between the two temperature measuring points H_b and the thermal heat conductivity of the employed aluminum of the bridge λ_A via Fourier`s Law of Conduction according to equation (2) [12]. In this case, the direction of the heat flow is not important. That is why equation (2) shows the absolute value of $\dot{Q}$.

$$\dot{Q} = \left| -\lambda_A \cdot A \cdot \frac{\Delta T_{\dot{Q}}}{H_b} \right| \tag{2}$$

Calculating the values of R_{th} for all different fluid layers makes them comparable among themselves and the different resistances can be evaluated. The detailed experimental setup and the different performed experiments are described within the next chapter.

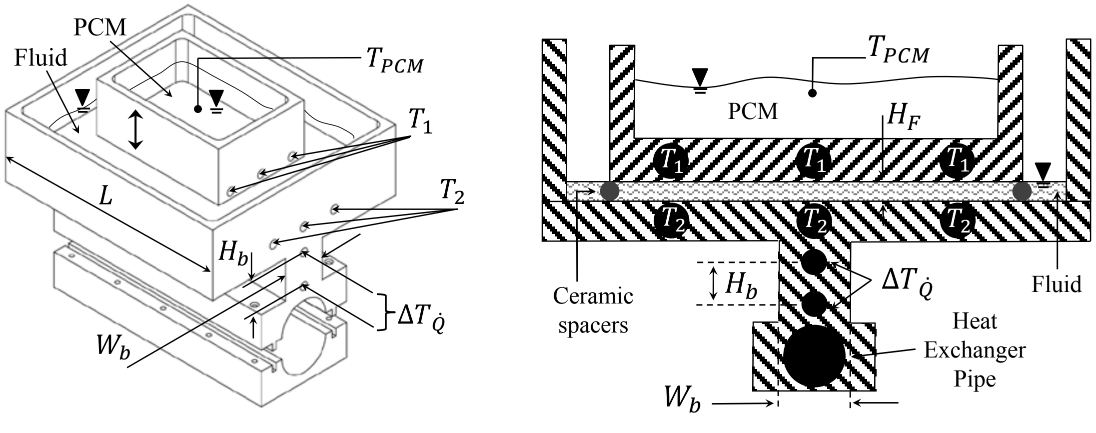

Fig. 4. (a) scheme of experimental setup for the examination of the heat transfer through the fluid layer; (b) schematic cross cut of the described experimental setup

2.2. Experimental setup and test execution

The forward velocity of the PCM containers is in the area of $10^{-5} m/s$ and therefore very small. It is not expected, that this movement has significant influence on the heat transfer through the thin fluid layer. That is why the experimental setup does not consider movement. The heat transfer over different heights of a fluid layer consisting of Hitec® is examined. For schemes of the experimental setup, see Fig. 4 (a) and (b).

The experimental setup consists of two main components. A bigger and a smaller trough made of aluminum AlMgSi1 are placed into each other. The bigger one is flanged to a pipe that is flown through by HTF. In this case the HTF is Syltherm 800®. The HTF is electrically heated to the claimed temperatures for charging and discharging, respectively. Inside the bigger trough, Hitec® as the fluid layer is put on the ground. The smaller trough is put into the fluid layer on ceramic sphere spacers, see Fig. 4 (b). These spacers can be changed and are responsible for an accurately defined distance between the two troughs, see Fig. 4 (b). The spacers are very small and therefore their influence on the heat transfer within the fluid layer can be neglected. Inside the smaller trough the above mentioned eutectic mixture of $NaNO_3$ and KNO_3 as storage material is located. Both trough bottoms are as thick as three calibrated resistance temperature detectors (RTDs) each can be completely inserted, see Fig. 4 (a) and (b). The temperatures in the bottoms are measured at three different positions and averaged for further processing. Due to the very good thermal conductivity of the employed aluminum, the resulting temperatures T_1 and T_2 are assumed to be the surface temperatures of the fluid layer at its top and bottom. This is how the temperature drop ΔT_F over the fluid layer can be measured. This temperature drop does not only depend on the thermal resistance of the fluid layer. It is also influenced by the heat flow $\dot{Q}$, that is transferred between the PCM in the smaller trough and the HTF inside the flanged pipe. This heat flow is calculated via $\Delta T_{\dot{Q}}$ that is determined at two measuring points inside a geometrically accurately defined bridge according to Fourier`s Law of Conduction, see Fig. 4 (a) and (b) and equation (2). During the experiments, the temperature of the PCM T_{PCM} inside the smaller trough is measured, see Fig. 4 (a) and (b). This temperature shows the beginning and the end of the phase change process inside the storage material. The necessary design details and material properties of the experimental setup including the employed materials are shown in Table 1.

The heat transfer over the fluid layer depending on its height H_F is examined according to the following procedure: The boundary conditions, like e.g. the starting temperature, the temperature of the HTF, the amount of PCM inside the small trough, the position of all RTDs, are kept constant. The only variable that is changed, is the height of the fluid layer $\mathrm{H_F}$, see Fig. 4 (b). The first experiment – as reference – is conducted without fluid layer and direct contact of the aluminum troughs with $H_F = 0mm\ (dry)$. In this case, the aluminum troughs are in touch with each other and the gaps in the contact area are filled with air. With this setup, the charging process is started and conducted with setting $T_{HTF,c}$ on the heat exchanger pipe via the HTF. This is continued until the PCM in the small trough is completely melted and a stationary state is established. After this, the PCM is discharged with $T_{HTF,d}$ in the heat exchanger pipe until the PCM is crystallized completely and again a stationary state is established. This is achieved for several cycles and the measured temperatures at all measuring points are averaged over them. After this reference experiment, the fluid layer is added into the bigger trough. First, the direct contact with fluid is measured the same way with $H_F = 0mm\ (wet)$. As a result, the air in the contact area gaps between the aluminum troughs is substituted by fluid. This setup is expected to be the best one because of the smallest distance between the aluminum components and the absence of air. The same cycles are examined like in the reference case. Additional experiments with the ceramic spacers are achieved leading to examination results with different heights of the fluid layer of $H_F = 0.5, 1, 2mm$. The influence of the fluid layer heights on the different resulting temperature drops over the fluid layer $T_1 - T_2$ in relation to the occurring heat flow $\dot{Q}$ can be observed immediately. Pictures of the experimental setup can be seen in Fig. 5 and Fig. 6. The results of the comparison of the different heights of the fluid layer and the resulting thermal resistance are shown in the following chapter.

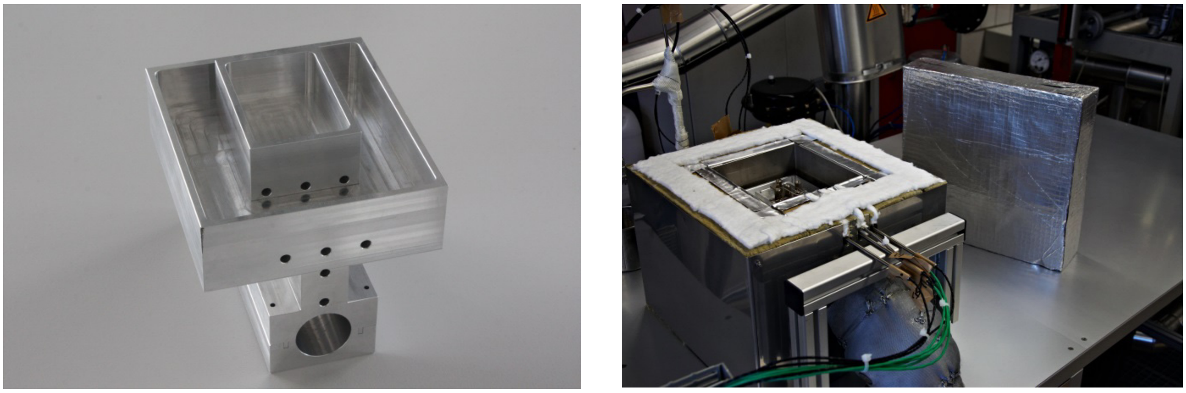

Fig. 5. (a) aluminum troughs with RTD boreholes; (b) isolated troughs connected to HTF pipe with inserted RTDs

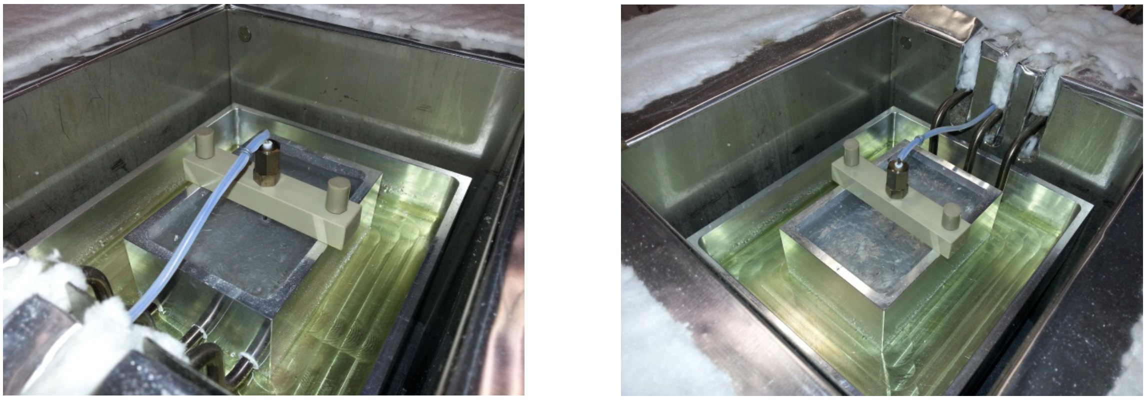

Fig. 6. Fluid layer and with PCM filled small trough together with temperature measure points T_1(3x) and T_{PCM} from the (a) front; (b) back

Table 1. Data of the experimental setup and material properties

Name	Variable	Value	Unit
Length of experimental setup	L	170	mm
Height of bridge	H_b	24	mm
Width of bridge	W_b	30	mm
Cross sectional area bridge	A_b	$5.1 \cdot 10^{-3}$	m^2
Height of fluid layer	H_F	$0\ (dry + wet), 0.5, 1, 2$	mm
Thermal conductivity aluminum	λ_A	180	W/mK
Thermal conductivity Hitec® (@222°C)	λ_F	0.49	W/mK
Thermal conductivity air (@222°C)	λ_{Air}	0.04	W/mK
Melting temperature fluid	$T_{m,F}$	$140 - 142$	$°C$
Melting temperature PCM	$T_{m,PCM}$	222	$°C$
Temperature HTF Charging/ Discharging	$T_{HTF,c}/T_{HTF,d}$	$232/212$	$°C$

2.3. Evaluation of the fluid layer

The experiments are conducted with the different heights of the fluid layer H_F as described before. Additionally, the direct contact of the small and big trough ($H_F = 0$) is evaluated with (wet) and without (dry) fluid. Exemplarily, the thermal resistances for each setup R_{th}, see equations (1) and (2), are shown in Fig. 7 for the charging process. At the beginning of the charging process, the HTF is heated sinus-shaped by the control system of the HTF providing system until it reaches the set value. That is why the resulting thermal resistances at the beginning also vary sinusoidal. After a while, R_{th} takes on a nearly constant value. The averaged values of these plateaus are used for comparison.

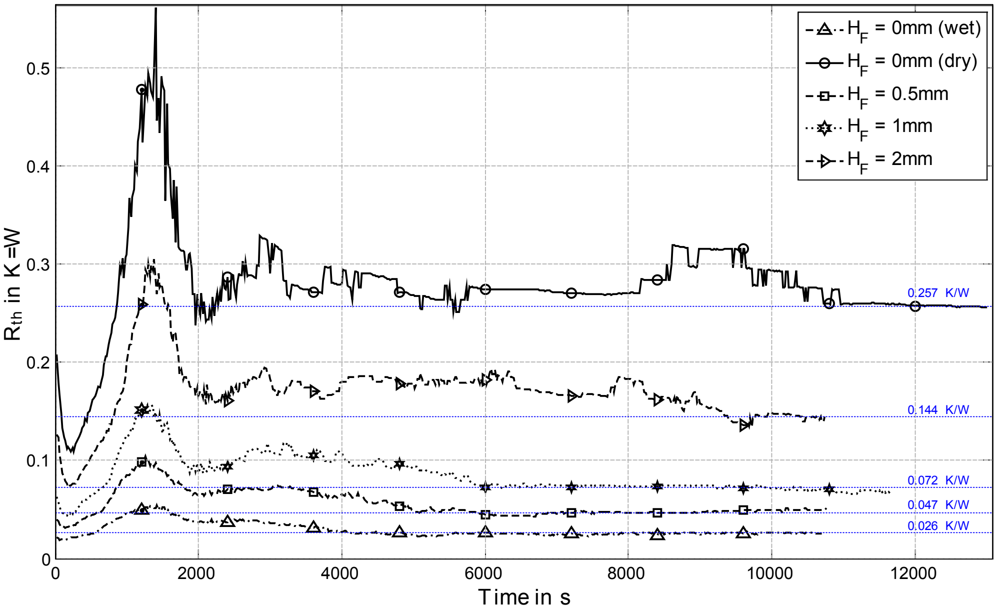

Fig. 7. Calculated thermal resistances R_{th} depending on different fluid layers while charging

Fig. 7 also shows the values of the thermal resistance of each experimental setup. The biggest $R_{th} = 0.257\ K/W$ shows the dry contact with air in the gaps, see Fig. 3 (a). On the other hand, the wet direct contact shows the best thermal contact with $R_{th} = 0.026\ K/W$. This fits with the expectations. Here, the height of the fluid layer is $H_F = 0$ due to direct contact. This fact minimizes the thermal resistance caused by heat conduction trough the fluid. Additionally, the gaps in the contact area are filled with fluid and not with air. These two facts result into an increase of the heat transfer by a factor of 9.9 comparing the worst (direct contact dry) and best (direct contact wet) cases with each other. Overall, the dry direct contact case also shows the worst heat transfer of all examined setups. Even the $H_F = 2mm$ case shows a reduction of R_{th} by 56% compared to the dry direct contact case. The other experiments are consistent, the bigger H_F, the bigger also the thermal resistance is.

By these experiments, two things are clearly shown: First of all, the employment of a fluid layer within the PCMflux concept to contact the storage material containers with the heat exchanger is meaningful. Moreover, the buckling of the containers seems – regarding heat transfer – not to be a critical issue with an implemented fluid layer. Buckling leads to an increase of H_F at the concerning areas. If no fluid layer was employed, the gap between the storage containers and the heat exchanger would be filled with air. This would lead to a significant increase of the thermal resistance. With Hitec® as fluid layer, the increase is damped in the same case. Therefore, the employment of aluminum foil as encapsulating material seems to be realizable. This leads to the minimization of the necessary auxiliary materials.

3. Conclusion

The PCMflux concept separates the storage material from the heat exchanger. The PCM is macroencapsulated into containers that are moved over the heat exchanger. Due to the movement, the thermal power of this latent heat storage system can be controlled accurately. The movement brings challenges with it, though. The thermal contact of the container and the heat exchanger has to be ensured. If the containers just had dry contact to the heat exchanger, the resulting thermal resistance at the contacting area is expected to be very high. Because of that, a central component of the PCMflux concept is a fluid layer between the containers and the heat exchanger. This fluid layer consists of the salt mixture Hitec®. An experimental setup was designed and constructed in order to examine the influence of this fluid layer on the heat transfer between container and heat exchanger. Different experiments with different fluid layer heights were conducted. The fluid layer turns out to improve heat transfer by a factor of 9.9 compared to the case with the absence of fluid. This result justifies the employment of a fluid layer. In a next step, the feasibility of the PCMflux concept will be shown experimentally with all important components, e.g. like the specifically designed heat exchanger and moving PCM containers.

Acknowledgements

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