High temperature latent heat storage

Dynamic High Temperature Latent Heat Storage Concept PCMflux: Results of the Experimental Proof-of-concept

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SUMMARY

Regenerator type storage systems using extended heat transfer surface represent the state-of-the-art in latent heat storage. These systems show a decreasing heat flux while discharging due to the coupling of heat exchanger and storage material. The PCMflux concept aims to overcome this disadvantage by the separation of power and capacity. Here, the storage material is filled into open containers made of aluminium that are moved over a heat exchanger. This offers the possibility to control the heat flux of the storage system while discharging by adjusting the velocity of the containers. The theoretical examination of this concept is finished and an experimental proof-of-concept was constructed. Within this paper, the PCMflux concept is briefly outlined and the experimental setup is described. First experimental results show both the feasibility of the PCMflux concept and the good agreement between theory and practice.

INTRODUCTION

With a rising integration of fluctuating renewable energy sources into the energy mix worldwide, energy storage becomes increasingly important. With large scale energy storage, electricity production can be adjusted to consumption. Thereby, supply and demand are smoothed and grid stability is improved.

One possibility to produce green and dispatchable electricity is the use of solar thermal power plants with large scale thermal heat storage. In this context, the combination of direct steam generation and the deployment of a latent heat storage promises good efficiencies. This is due to small occurring temperature differences between the phase change material (PCM) and the heat transfer fluid (HTF).

However, the state-of-the-art latent heat storage has a disadvantage, where the heat exchangers are immersed directly into the PCM. While discharging, the crystallizing PCM covers the heat exchanger and builds up a growing isolating layer. This results in a significant heat flux drop over time. Details about this storage systems can be found in literature (Laing et al. 2011a, 2011b, 2011c).

The presented work is part of the "nextPCM" project supported by the German Federal Ministry for the Environment, Nature Conservation and Nuclear Safety. Its main aim is the development and demonstration of an innovative latent heat storage concept named PCMflux that overcomes the heat flux drop while discharging and stays fully controllable throughout operation. Within this paper, the PCMflux concept is described briefly and the first results of the experimental proof-of-concept are given.

METHODS

The PCMflux concept faces the challenge of decreasing heat flux while discharging by separation of power and capacity (Steinmann, 2009). This is realized by the physical separation of PCM and heat exchanger. Thereby, the PCM is filled into thin aluminium foil containers that can be moved slowly over a locally fixed heat exchanger. The heat exchanger consists of a heat exchanger tube and a connected aluminium fin, see Figure 1. These two components are referred to as a heat exchanger. While passing the heat exchanger, the PCM changes phase completely.

In the experimental proof-of-concept the eutectic mixture of sodium and potassium nitrate $NaNO_3(46wt\%) - KNO_3(54wt\%)$ with a melting temperature of $T_{m,PCM} = 222\ °C$ is employed as a PCM.

To avoid dry contact and the resulting significant thermal resistance between containers and heat exchanger, an intermediate fluid is introduced onto the heat exchanger. As this fluid, Hitec® is used. It is a commercial nitrate salt mixture with a melting temperature of $T_{m,F} = 140\ °C - 142\ °C$ (Janz and Truong, 1983; Raade and Padowitz, 2011). The intermediate fluid layer stays liquid throughout discharging and charging the PCM due to its significantly lower melting temperature than the PCM. Therefore, the movement of the PCM containers is not interfered with. The behavior of the thermal resistance between the heat exchanger and containers with and without fluid layer for different process variables was examined experimentally. The employment of the fluid layer increases heat transfer between PCM and heat exchanger by the factor of 9.9 compared to dry contact. Details about this study are given in (Pointner et al., 2014c). To keep the fluid in its position the heat exchanger is bowl-shaped, for details see Figure 1.

The containers are connected to each other with a wire system. These wires are made of thin and flexible steel cables. To move the PCM containers into one direction, an electrical positioning motor pulls the wires to make the containers move. Small velocities in the range from $v = 3 \cdot 10^{-5} m/s$ up to $v = 5 \cdot 10^{-4} m/s$ are realized by the implementation of a gear with a transmission ratio of $i = 625.73 : 1$. The integrated control mechanism in the motor allows the minimization of the error to less than 1 %.

For charging, the containers are moved to the right side within the experimental setup. In this case, the containers enter the heat exchanger on the left side, see Figure 1, and sink down to the bottom of the fluid wetted heat exchanger. After a complete phase change on top of the heat exchanger, the containers are moved out of the heat exchanger and are stored on a guide system. For the discharging process, the movement of the storage material containers is achieved into the other direction.

Choosing a specific forward velocity v that depends on different process, geometry and material variables such as temperature difference between PCM and HTF (ΔT), heat of fusion and size of heat exchanger, results in the establishment of a quasi-stationary phase change interface inside the moving PCM. As soon as this state is developed, a constant thermal power output while discharging is realized. The heat flux thereby can be controlled accurately by the forward velocity of the PCM containers. The PCMflux concept and the general correlation between forward velocity and resulting heat flux via a dimensionless number K_{Flux} is described in detail in (Pointner et al. 2014a, 2014b).

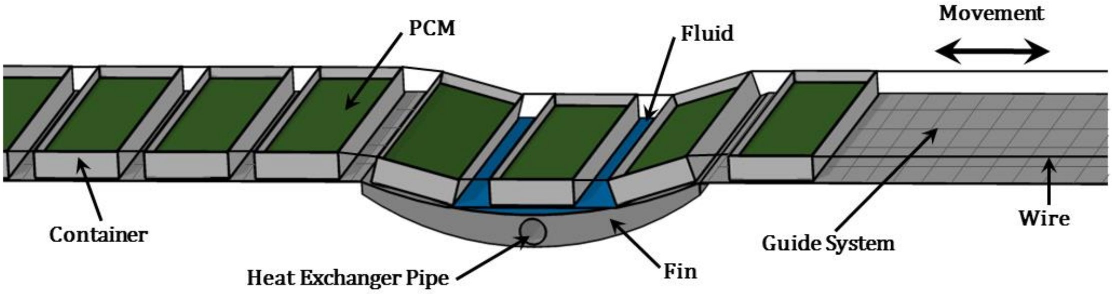

Figure 1: Scheme of one PCMflux module with main components

The principle system shown in Figure 1 is isolated and connected to a thermal oil supplier unit. The thermal oil is used as a HTF instead of a water-steam system for the experimental proof-of-concept in order to reduce possible sources of errors. The experimental setup has a length of $1.45\ m$, a width of $0.52\ m$ and a height of $0.4\ m$ including insulation. The position of the phase change interface inside the PCM containers is observed by a thermographic camera which is mounted above the experimental setup. A window of $ZnSe$ is put into the top insulation cover above the heat exchanger. This crystal allows the infrared camera the detection of the infrared radiation inside the experimental setup and makes the observation of the phase change interface of the PCM possible. An image of the experimental setup without top cover insulation is shown in Figure 2 (a). Additionally, an image of the PCM filled aluminium foil containers is given in Figure 2 (b).
The results presented in the following chapter base on an exemplary discharging process with a PCM height inside the containers of $5\ mm$, an effective temperature difference between PCM melting temperature and HTF temperature of $\Delta T = 6.2\ K$ and a forward velocity of the containers of $v = 1.7 \cdot 10^{-4} m/s$.

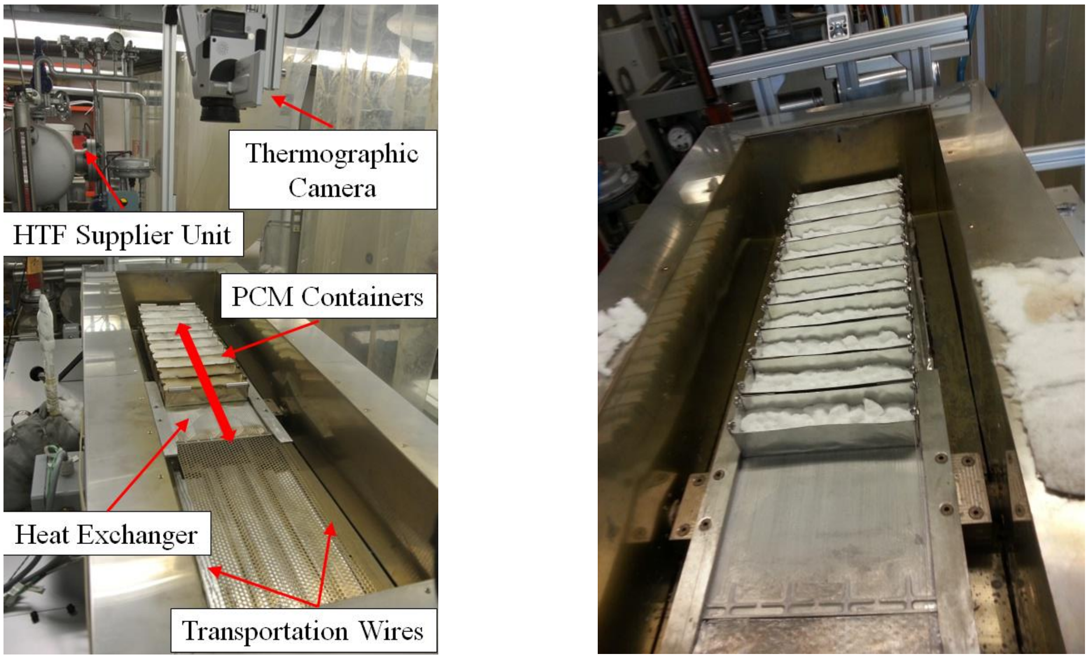

Figure 2: (a) Picture of the experimental setup with main components of the PCMflux concept; (b) With PCM filled aluminum foil containers entering the heat exchanger

RESULTS AND DISCUSSION

At the beginning of the discharging process, all of the PCM inside the containers is completely melted and has a temperature slightly above the melting temperature of $T = 226\ °C$. All containers are located on one side of the experimental setup on the guide system, see Figure 1 and Figure 2. The discharging temperature of the HTF is set to its discharging value to obtain a temperature difference of $\Delta T = 6.2\ K$. After reaching a constant temperature, the electrical motor is switched on and the PCM containers start moving and the thermographic camera starts recording.

The results show the establishment of a quasi-stationary state resulting in a locally-fixed phase change interface inside the PCM containers even though the containers are moving. An original image from the infrared camera of the established quasi-stationary state can be seen in Figure 3. The infrared camera only measures a narrow section in the middle of each PCM container into the direction of movement. Due to connected heat losses, the area of measurements through the $ZnSe$-crystal is minimized. The centred area of the containers is the most suitable for measurements, since boundary effects have lowest influence there. The crystal and measurement area covers the whole length of the heat exchanger. Both the entrance and the exit areas, where the PCM containers enter and leave the heat exchanger, are directly on the borders of the image. Figure 3 shows four PCM containers schematically located on the heat exchanger with the original infrared image of the measurement area placed in the middle to clarify the position of the measurement.

The containers move from the right to the left over the heat exchanger and change phase. Right after entering the heat exchanger on the right of the infrared picture in Figure 3, the PCM is fully liquid. This can be seen clearly by a smooth temperature distribution within the right PCM container signifying a consistent surface that is only possible for liquid PCM. On the way to the left, the PCM starts to change phase. This is signalized by a rougher temperature distribution in the three left containers with crystallizing PCM. While changing phase, the emission coefficient of the PCM also changes. This effect is detected by the thermographic camera with a fictive increase of temperature, turning the colour from orange to red. This effect indicates the beginning of phase change, while in reality there is no increase of temperature. After a complete phase change, the PCM cools down until the colour turns over white to blue. Right at this point, the PCM can be viewed to be solidified completely. The thermographic camera is calibrated for liquid PCM, the absolute values of the temperature of the solid PCM deviates from reality due to the change of the emission coefficient. The emission coefficient is higher for solid PCM than for liquid PCM and since higher emission coefficients lead to higher temperatures, measured temperatures underneath the melting temperature show solidified PCM. Moreover, the complete solidification of the PCM was checked optically during the experiments.

Since the infrared image shows the quasi-stationary state, the image does not change significantly with time. Mainly, the only change is the moving aluminium foil walls of the PCM containers. That is why a constant heat flux over time is achieved. By varying the forward velocity, the position of this phase change interface can be adjusted. Since the velocity of $v = 1.7 \cdot 10^{-4} m/s$ was calculated via K_{Flux} as the maximum one for this circumstances, the position of the phase change interface is expected to be at the end (here: on the left side) of the heat exchanger (Pointner et al. 2014a, 2014b). This can be seen in Figure 3. Increasing the velocity in this case leads to an incomplete phase change, since the PCM does not have enough time to change phase while being on the heat exchanger. With a decrease in forward velocity, however, the position of the phase change interface at the quasi-stationary state can be moved to any position closer to the right side. In this case, the heat transfer area of the heat exchanger is no longer used completely and the heat flux of the storage system decreases. But here again, the resulting heat flux is constant over time. Consequently, the heat flux of any PCMflux module configuration can be controlled by moving the quasi-stationary phase change interface along the heat exchanger by varying the forward velocity v of the PCM containers. This leads to a fully controllable latent heat storage system with constant heat flux over the whole operational time at the desired levels.

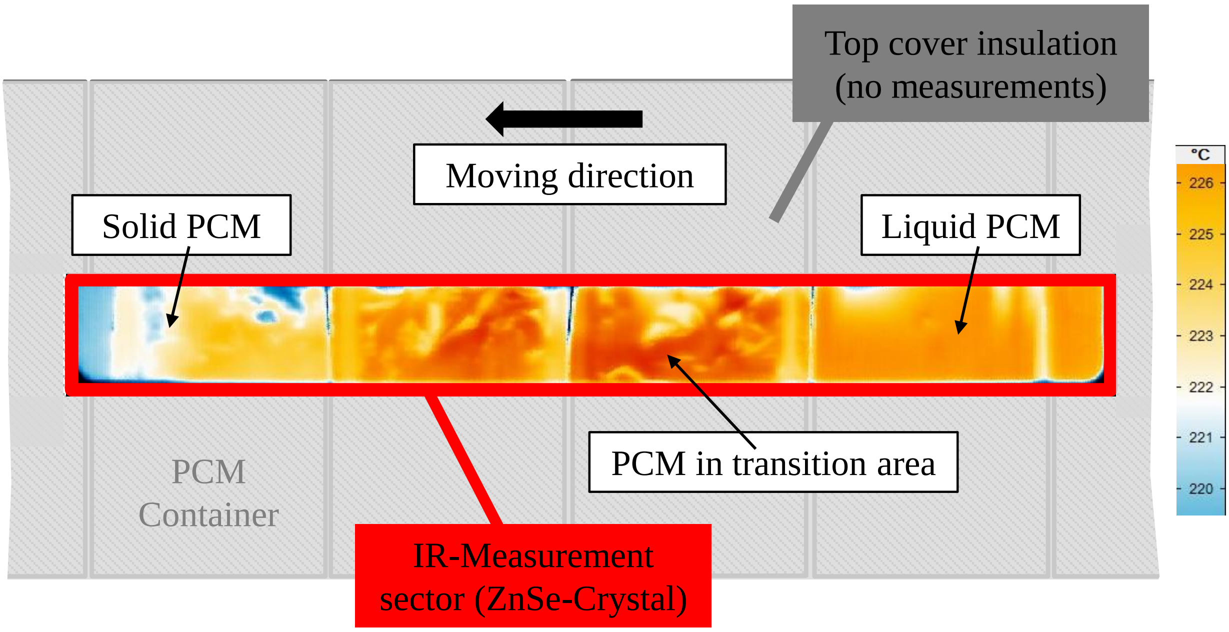

Figure 3: Infrared picture of quasi-stationary state with steady phase change interface and the location of the narrow ZnSe-crystal for IR-measurements in the middle of the PCM containers

CONCLUSIONS

Within this paper, the principles of the PCMflux concept are briefly described. In a second step, the experimental setup for the proof-of-concept is outlined and the methodology for observing the phase change interface is given. The experimental proof-of-concept shows the feasibility of the PCMflux concept and the agreement of the developed theory with reality. The PCMflux concept allows the full control of the heat flux over the whole operational time of the storage system. As next steps, experiments at the described experimental setup will be completed and evaluated with a high variation of different parameters. Moreover, a pilot plant of the PCMflux concept with heat fluxes of up to 5 kW is being planned and constructed.

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REFERENCES

Janz, G. J., Truong, G. N. (1983). Melting and Premelting Properties of the KNO3-NaNO2-NaN03 Eutectic System. *Journal of Chemical & Engineering Data*, *28*, 201–202.

Laing, D., Bahl, C., Bauer, T., Lehmann, D., Steinmann, W.-D. (2011a). Thermal energy storage for direct steam generation. *Solar Energy*, *85*(4), 627–633. doi:10.1016/j.solener.2010.08.015

Laing, D., Bahl, C., Fiß, M., Hempel, M., Meyer-Grünefeldt, M., Eickhoff, M., Stückle, A. (2011b). Test and evaluation of a thermal energy storage for direct steam generation. In *SolarPACES*. Granada, Spain.

Laing, D., Eickhoff, M., Fiß, M., Hempel, M., Meyer-Grünefeldt, M. (2011c). Test results of a storage system for parabolic trough power plants with direct steam generation. In *5th International Conference on Energy Sustainability*. Washington DC, USA.

Pointner, H., Steinmann, W.-D., Eck, M. (2014a). Introduction of the PCM Flux Concept for Latent Heat Storage. *Energy Procedia*, *57*, 643–652. doi:10.1016/j.egypro.2014.10.219

Pointner, H., Steinmann, W.-D., Eck, M. (2014b). PCMflux as a fully controllable dynamic latent heat storage system. In *Eurotherm Seminar N99 - Advances in Thermal Energy Storage*. Lleida, Spain.

Pointner, H., Steinmann, W.-D., Eck, M. (2014c). Separation of Power and Capacity in Latent Heat Energy Storage. In *SolarPACES Concentrating Solar Power and Chemical Energy Systems*. 16.09.-19.09.2014, Beijing, China.

Raade, J. W., Padowitz, D. (2011). Development of Molten Salt Heat Transfer Fluid With Low Melting Point and High Thermal Stability. *Journal of Solar Energy Engineering*, *133*(3). doi:10.1115/1.4004243

Steinmann, W.-D. (2009). Speichersystem zur Speicherung thermischer Energie. Germany. Patent: DE 10 2004 020 993 B4 2009.12.31