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Experimental demonstration of an active latent heat storage concept

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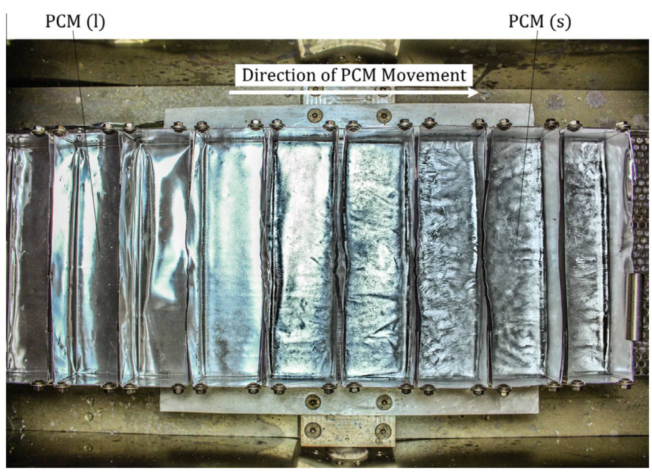
HIGHLIGHTS

- A novel active latent heat storage concept is described and experimentally demonstrated.
- The storage material is mechanically separated from the heat exchanger and can be moved.
- A constant heat flux during the discharging process is achieved.
- The heat flux is controlled by adjusting the storage material's forward velocity.
- The underlying theory fits well to the experimental results.

GRAPHICAL ABSTRACT



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ABSTRACT

Latent heat storage allows efficient energy storage in systems with isothermal processes. The low thermal conductivity of cost-effective storage materials is the main challenge in the development of latent heat storage systems. Most of these systems developed so far use extended heat transfer surfaces to ensure sufficient heat transfer rates. The PCMflux concept described in this paper is based on the transport of the storage material across the heat transfer surface. The aim of this approach is to avoid the blockage of the heat transfer surfaces by solidified storage material. The paper gives an overview of the current development of the PCMflux concept including the theoretical analysis and the experimental proof-of-concept.

1. Introduction

The main advantage of latent heat storage systems is the ability to store heat in a narrow temperature range. This allows the effective storage in applications that include isothermal processes, such as steam processes in industry or in power plants [1]. The option to integrate storage capacity is a key feature of solar thermal power plants. If steam is used as heat transfer medium in the solar absorbers, latent heat storage systems enable a high second law efficiency. In the temperature range from 150 °C to 350 °C, nitrate salts are often used as phase change material (PCM) [1–5]. While these materials are cost attractive, they have a low thermal heat conductivity [6–8] which causes performance problems while operating the storage system. While discharging, the PCM first crystallizes in regions close to the heat exchanger and sticks on

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Nomenclature

A_C	cross-sectional area of the PCM container (m^2)
A_F	area of the fluid layer on the heat exchanger (m^2)
A_P	inner area of heat exchanger pipe (m^2)
A_{PCM}	cross-sectional area of the PCM (m^2)
c_C	specific heat capacity of the container material (J/kg K)
c_{PCM}	specific heat capacity of the PCM (J/kg K)
d_P	diameter of the heat exchanger pipe (m)
H_{PCM}	height of the PCM (m)
K_{Flux}	dimensionless number to describe the PCMflux system (–)
L	heat of fusion of the PCM (J/kg)
l	liquid phase
P_{Fin}	perimeter of the heat exchanger fin (m)
$\dot{Q}$	heat flow (W)
$\dot{q}$	inner heat exchanger pipe surface related heat flux (W/m^2)
$\dot{q}_{max}$	nominal heat flux of a specific module configuration (W/m^2)
S_{Fin}	length of the heat exchanger fin (m)
s	solid phase
$T_{m(,F)}$	melting temperature of the PCM (Fluid) (°C)
v	forward velocity of the PCM (m/s)
v_{max}	nominal PCM forward velocity of a specific module configuration (m/s)
W_C	width of the container wall (m)
W_F	width of the fluid layer (m)

Greek symbols

ρ_C	density of the container material (kg/m^3)
ρ_{PCM}	density of the storage material (kg/m^3)
ΔT	temperature difference (K)

Abbreviations

HTF	heat transfer fluid
HTS	heat transfer structure
PCM	phase change material
SHE	screw heat exchanger
QP	quasi-stationary phase change interface
ZnSe	zinc selenide

it. With the ongoing discharging process, this layer of frozen PCM around the heat exchanger grows, as shown in Fig. 1. Within this solid layer, no convection effects can improve heat transfer and heat conduction represents the dominating heat transportation mechanism. Here, the poor thermal heat conductivity becomes important. With a growing solid PCM layer around the heat exchanger, the thermal resistance between the liquid PCM and the heat transfer fluid (HTF) inside the heat exchanger increases steadily. This results in a declining heat flux during the discharge process [3,9].

Various concepts have been suggested to overcome the limitation resulting from the low thermal heat conductivity of the PCM by enlarging the heat transfer area by the deployment of fins [5,10–16]. Among others, some concepts address the challenge with increasing the effective thermal heat conductivity of the PCM either by integrating the PCM into highly conductive matrices [3,17–22] or improving heat transfer by the deployment of heat pipes [23–26]. Most of these concepts can be considered as passive PCM storage systems using heat exchangers embedded into the storage material. With the enlargement of the capacity of such storage systems, the heat transfer structure (HTS) inside the PCM must also be enlarged in order to secure a sufficient heat transfer. Therefore, no considerable cost savings can be expected for large scale latent heat storage systems of such a type.

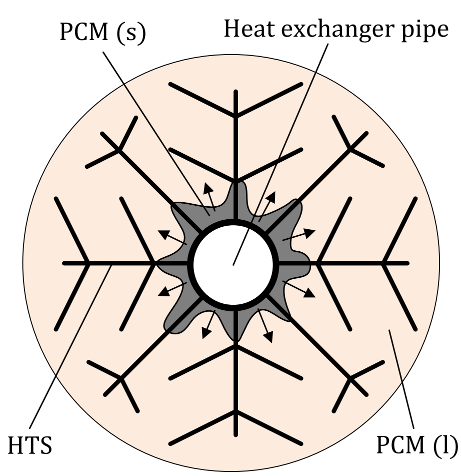

Fig. 1. Cross-section of an example of a latent heat storage module with heat exchanger pipe, attached heat transfer structure (HTS) and the growing layer of solidified PCM during discharging.

In active PCM storage systems the storage material is separated mechanically from the heat transfer section. During charging and discharging the storage material is transported across thus section and is thereby independent of the capacity of the storage system. Essential for active PCM storage systems is the close thermal contact in the heat transfer area. This area must not be covered by solidified PCM.

One active latent heat storage system is the *Screw Heat Exchanger (SHE)* concept developed by Zipf et al. [27]. Here, the PCM is transported steadily by a rotating double screw system from one end to the other. While passing the screw heat exchangers, the PCM changes phase. The screw flights of the heat exchangers scratch off the crystallized PCM from each other and the establishment of a growing layer of solid PCM is avoided.

The novel active latent heat storage concept described and experimentally demonstrated in this article is called *PCMflux*. It aims for a constant and controllable discharging heat flux at a high level with a potentially low deployment of auxiliary materials. It represents a new active latent heat storage concept and its application is thereby not limited to solar thermal power plants. Without significant changes in its design, it also comes into consideration for raising the energy efficiency of e.g. industrial processes in a wide range of temperatures with a linked HTF system that undergoes a change of aggregate state.

2. The PCMflux concept

To overcome the heat flux drop while discharging within the PCMflux concept, the storage material (capacity) is mechanically separated from the heat exchanger (power) [9,28]. Starting from the state-of-the-art in latent heat storage, the stages in the development of the PCMflux concept are schematically visualized in Fig. 2. Fig. 2(a) shows a cross-sectional cut of a heat exchanger pipe