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Experimental characterization and simulation of a hybrid sensible-latent heat storage

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HIGHLIGHTS

- A new versatile sensible-latent heat storage concept was designed.
- An inverted shell-and-tube heat exchanger with the PCM inside the tubes was used.
- We characterized a prototype containing 208.2 kg HDPE and 515.1 kg thermal oil.
- Two computer models were developed showing excellent agreement with experiments.
- A cost calculation was performed and two promising applications were described.

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ABSTRACT

Versatile and economically competitive thermal energy storages are necessary to fulfill the widely differing requirements for storages applied in renewable energy systems, process heat, district heating, power generation and domestic heating. We present the concept of a hybrid sensible-latent heat storage based on an adapted commercial shell-and-tube heat exchanger. The phase change material (PCM) is encapsulated within the tubes and thermal oil serves as sensible heat storage as well as the heat transfer medium. We designed and built a prototype using high density polyethylene (HDPE) as PCM and characterized the storage on a dedicated test rig at AIT. Energy capacities and power profiles are presented for different mass flows and (dis)charging temperatures. Two physical models were developed and implemented using the Modelica language. Dymola was used to simulate the behavior of the prototype storage. Very good agreement was achieved between simulation and experiment. Using the models, we studied the heat transfer within the storage in detail, which enabled us to present how to adapt the storage geometry and PCM properties to cover a broad range of applications. We discuss storage costs and calculate material costs per stored kilowatt-hour for different PCM-thermal oil volume ratios as a function of the tube outer diameter. Finally, we highlight the main advantages and design freedoms of our concept and describe concrete application scenarios in district heating and process heat.

1. Introduction

Energy storages are necessary to increase the share of intermittent renewable energy systems, increase energy efficiency and thus mitigate CO_2 emissions [1,2]. A substantial fraction of the energy demand is thermal energy. Process heat is required in many industries to produce goods and building climatization in omnipresent. Heating networks in industries as well as urban regions distribute this heat generated by central power plants or decentralized heating units. In most cases the heat demand is not constant, but various peaks are present. If renewable intermittent energy sources are utilized, there is often a big mismatch between heat supply and demand. Thermal energy storages are necessary to bridge this temporal mismatch and are utilized for peak shifting and demand side management [3–5]. In addition, they enable waste heat recovery in different industrial processes and sectors, which is reviewed by Miro et al. [6] including mobile thermal storage [7,8]. Thermal energy storages are also investigated in combinations with heat pumps to increase their efficiency [9,10] and offer concentrating solar power plants an advantage over photovoltaic systems by allowing electricity production when the sun does not shine [11–13]. Recently thermal energy storage have also been investigated

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Nomenclature

α	heat transfer coefficient (W/m^2 K)
λ	thermal conductivity (W/m K)
μ	dynamic viscosity (kg/m s)
ρ	density (kg/m^3)
A	surface area (m^2)
D	diameter of tube (m)
h	phase change enthalpy (kJ/kg)
l	length of tube (m)
m	mass (kg)
Q	heat (kW h)
r	radius (m)
T	temperature (°C)
t	time (s)
v	velocity (m/s)
c_p	constant pressure specific heat (J/kg K)
$\dot{m}$	mass flow rate (kg/s)
$\dot{Q}$	heat transfer rate (kW)
$\dot{q}$	heat flux (W/m^2)
Gz	Graetz number (–)
Pr	Prandtl number (–)
Re	Reynolds number (–)

Subscripts

amb	ambient
avg	average
c	center
cryst	crystallization
f	phase change front
i	inner
in	inlet
melt	melting
o	outer
out	outlet
st	steel
t	tube
vol	volume

in micro-CHP plants to optimize costs and revenues [14] and to optimize the performance of a bank of chillers [15].

Latent heat storages offer large energy densities without high pressures as in steam accumulators or pressurized water tanks. This technology is a promising candidate, especially for temperatures above 100 °C. Many different storage concepts have been investigated for a wide range of application such as concentrated solar power [16–21], industrial waste heat recovery [22–28] and solar cooling [29,30].

Among the different investigated concepts [31] shell-and-tube heat exchangers offer an interesting opportunity for latent heat storages. In most cases a configuration was chosen, where the phase change material is located on the shell side and the heat transfer fluid is flowing within the tubes. There have been many theoretical studies: Tay et al. [32] and Fornarelli et al. [33] used computational fluid dynamics (CFD) to study melting, Pirasaci and Goswami [34] and Tehrani et al. [35] analyzed different storage geometries for power plants. Bai et al. [36] focused on the economics. The effect of introducing fins to enhance heat transfer was investigated by different authors [37,38] and the effect of the PCM thermophysical properties was studied in [39]. Experimental studies were performed studying the phase change process in single tubes [40–43]. Lab-scale storages were built and characterized by Lopez et al. [44] and Tay et al. [45].

Almost no work was done on the inverted configuration, where the PCM is inside the tubes and the heat transfer medium is flowing on the shell side, although such a concept offers interesting opportunities. Especially, since it is easy to vary the latent and sensible energy contributions over a wide range and to realize hybrid sensible-latent heat storages using this configuration. In such storages, one can benefit from both, the high energy density of PCMs and the high powers of the sensible storages. As is emphasized in [46,47] a big advantage is that the PCM allows the reduction of the quick drop of the outlet temperature of sensible storages during discharging. In addition, Geissbühler et al. [48] show that it is also possible to reduce the fast power decrease of sensible storages by including PCMs. Furthermore, inverted shell-and-tube heat exchangers enable the macro-encapsulation of the PCM within the tube in an efficient way and generally have better heat transfer characteristics on the heat transfer fluid side (cf. [49]). The opportunities of inverted shell-and-tube sensible-latent heat storage are discussed in more detail in the next section.

To our best knowledge only Zhang, Ma and Xiao investigated a PCM storage that is related to the inverted shell-and-tube configuration. They presented fluid dynamics simulations [50,51] and built and characterized a lab-scale storage [52]. They encapsulated an eutectic mixture of $NaNO_3$ and KNO_3 and a nickel foam to improve heat transfer into stainless steel containers. These containers were immersed in the heat transfer fluid (thermal oil) and placed inside an insulated tank.

In this work, we present for the first time a fully integrated solution of a hybrid sensible-latent heat storage based on an inverted shell-and-tube configuration. We redesigned a shell-and-tube heat exchanger, encapsulating the PCM within the tubes. The thermal oil on the shell side, simultaneously serves as a sensible heat storage and heat transfer medium. The whole storage was produced by an industrial company using professional and standardized manufacturing techniques. In that way, we ensure high prototype quality, scalability for later commercial storages and a short time-to-market enabling CO_2 savings quickly. It will be possible to manufacture storages of several meters in diameter and length containing tons of PCM with the very same production methods.

2. Experimental investigation

2.1. Storage design

As outlined in the introduction, most authors investigating shell and tube heat exchanger in PCM storages placed the PCM on the shell side and the heat transfer fluid flows within the tubes whereas in our design the situation is inverted. Depending on the needs of the application (energy density, power profile), one design might be superior to the other.

- The volume share of PCM in our configuration is limited to a maximum of 90% in a densely packed staggered tube arrangement. Necessary gaps between the tubes for heat transfer fluid flow reduce the PCM volume further (cf. Fig. 2).
- The number and length of weld seams depends on the storage capacity and power profile. As this can be a major cost driver, a careful assessment has to be performed for each case.
- In our design, as the heat transfer fluid is outside of the cylindrical tubes containing the PCM, there is a large heat transfer area in the beginning. It decreases as the phase front moves towards