Journal of Energy Storage 17 (2018) 56–62

Contents lists available at ScienceDirect

Journal of Energy Storage

journal homepage: www.elsevier.com/locate/est

Parametric study of the thermocline filler concept based on exergy

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ARTICLE INFO

Article history:
Received 2 October 2017
Received in revised form 8 January 2018
Accepted 15 January 2018
Available online xxx

Keywords:
Thermal energy storage
Molten salt
Parametric study
DLR
TESIS

ABSTRACT

In this work, an extensive parametric study of the molten salt thermocline storage concept with filler is presented. The parametric study is coupled with an optimization routine, allowing a better comparison, since it finds only those storage configurations, which can directly substitute the two-tank system in a given power plant. Results show that, compared to the two-tank molten salt system, the thermocline technology achieves high exergetic efficiency at only slightly increased storage volume size and a huge decrease in salt inventory.

1. Introduction

Storing thermal energy in liquid molten salts provides an easy to handle and cost effective solution for thermal energy storage at high temperatures. The technology offers great potential for the energy transition in Germany. Examples are the improved use of waste heat from industrial processes or increasing the flexibility of power stations and cogeneration, as well as the conversion and storage of fluctuating surplus electricity from renewable energy sources. Proven technology, low cost salts as storage materials, excellent heat transfer rates and operation at ambient pressure are some of the key attributes for molten salt technology. By embedding a low cost solid filler material into the molten salt storage tank, further cost reductions of up to 33% can be achieved [1].

The thermocline concept with filler has already been demonstrated in the 80 s in a large scale of 170 MWh_{th} at the SolarOne power plant [2] (Fig. 1, left). This system used thermal oil as HTF and rocks as filler material. Experimental results with molten salt, but in a smaller scale of 2.3 MWh_{th} have been presented by Sandia (Fig. 1, right). In this test facility a ternary molten salt mixture ($44\%_{wt}$ $Ca(NO_3)_2$, $12\%_{wt}$ $NaNO_3$, $44\%_{wt}$ KNO_3, similar to Hitec XL) has been used along with quartizite rocks and silica sand at temperatures of up to 500 °C. During operation, part of the calcium nitrate transformed to calcium carbonate, particularly in the cold tank which had been open to atmosphere. However, the scaling was beneficial for the stability of the rocks, shielding them from degradation [3].

A mid-sized experiment with 3 m height, 1 m diameter and thermal oil operating at up to 350 °C has been investigated at CEA [5]. CEA has also successfully demonstrated a complete plant, consisting of a fresnel collector, an organic rankine cycle (ORC) and a thermocline thermal storage with 30 m^3 in volume [6]. In both cases thermal oil as HTF has been used. Another mid-sized experiment, similar to that of CEA, was developed in France as well: At the PROMES CNRS Laboratory in Odeillo, a thermocline tank with filler has been integrated to a parabolic trough loop with an ORC. The tank is 3 m in height and 1.3 m in diameter (4 m^3) [7,8].

At DLR in cologne a large scale *Test facility for thermal Energy Storage In molten Salts* (TESIS) has been set up. The volume of the storage tank is 22 m^3 and can be equipped with three equally sized baskets, holding the filler material. An illustration of the interior is shown in the left picture of Fig. 2. The storage tank can be supplied with molten salt at a maximum temperature of 560 °C and a mass flow of 4 kg/s. Hot and cold molten salt are held by two separate storage tanks, visible on the right picture in Fig. 2. By using these storage tanks, a powerful auxiliary heater and cooler can be avoided, making the plant energy efficient. In fact, only 125 kW heating and cooling power are necessary for adjusting temperatures.

Besides the experimental work, several theoretical investigations have been done. At CIEMAT simplified models for system simulations [9] and possible operation strategies [10] have been theoretically investigated. An analytic model developed at EEWRC has been used for the application of sensivity analysis for thermocline optimization [11].

As can be seen, technological challenges arise mainly from the chemical stability of the molten salt/filler system and the necessity

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https://doi.org/10.1016/j.est.2018.01.009

Nomenclature

A_0	Cross sectional area [m^2]
d_{part}	Particle diameter [m]
h	Specific enthalpy [h]
$\Delta E'_{\text{stor,nom}}$	Initially available exergy [W]
$\Delta E''_{\text{stor}}$	Regained exergy during discharge [W]
L_{stor}	Storage tank length [m]
D_{stor}	Storage tank diameter [m]
$\dot{m}$	Mass flow rate [kg/s]
m	Mass [kg]
n	Integer number [−]
T	Temperature [°C]
ΔT_e	Permitted change in exit temperature [K]
x,y,z	Artesian axis direction [m]
Δp	Pressure loss [bar]
s	Specific entropy [J/kgK]
t	Time [s]
t'_{e}	Storage time [s]
v	Velocity [m/s]
V_{stor}	Storage volume [m^3]
$\dot{Q}$	Thermal power [W]
$\dot{Q}_f'''$	Volumetric heat generation density [W/m^3]
$\dot{Q}_{\text{th}}$	Thermal power of the power block [W]

Special characters

α	Heat transfer coefficient [W/m^{2}K]
ε	Porosity [−]
λ	Thermal conductivity [W/mK]
μ	Dynamic viscosity [Pas]
ρ	Density [kg/m^3]
Ξ	Exergy regain [−]
ϑ	Weighting factor [−]

Subscripts

e	End
eff	Effective
f	Fluid
in, out	Inlet/outlet position
init	Initial value
nom	Nominal
s	Solid
set	Set value
th	Thermal
vol	Volumetric
wt	Weight

in finding optimized operation strategies for such highly dynamic systems.

2. Parametric study of a large scale thermocline system

For the parametric study, a thermocline storage volume with solarsalt as HTF and basalt rocks as filler is considered. The thermophysical properties of solarsalt are taken from Bauer et al. [12], whilst properties for basalt can be found in Vosteen et al. [13]. For the attached process, a parabolic trough thermal power plant with 235 MW$_{\text{th}}$ nominal thermal power and a corresponding mass flow rate of $\dot{m}_{\text{f}} = 581.85\text{kg/s}$ is assumed. Two different cases are considered, one where the storage time during charging ($t'_{\text{e,set}}$) is fixed to 8 h and one where it is fixed to 12 h. The superscript ′ generally indicates the charging cycle, whereas ″ the discharging cycle.

The input values for the simulation are summarized in Table 1.

2.1. Identification of relevant parameters

For a thermal energy storage system, there are generally several major influencing parameters. All parameters are summarized in Table 1.

From the system point of view, the permitted change in exit temperature has the most significant impact, since the system connected to the storage system must cope with the changing temperatures. However, there is also a significant impact on the utilization of the storage volume. From analytical solutions, it is known, that the thermocline region does not remain stable. Instead, it will grow with a rate which is proportional to square root of time [14]. In the moment of switching from charging to discharging (or vice versa), higher temperature differences between fluid and packing in the inlet region occur. These higher temperature differences cause an increased heat transfer. Thus, the packing can reach fluid temperature within a short distance along the flow direction. This shrinks the thermocline region in the beginning of a new charging or discharging period. Hence, the temperature differences between fluid and packing are directly linked to the permitted change in exit temperature (ΔT_{e}). The highest differences occur, when the storage volume has been heated to uniform temperature beforehand, as it happens at the initial charging cycle. In this case, the shrinking effect on the thermocline region is the highest, whereas if ΔT_{e} is small, the growth of the thermocline region is almost not affected. Fig. 3 illustrates this in an example calculation for the storage system of the TESIS test facility. The thermocline region is compact after the end of the first cycle, the only difference is, that in the case with 30 K ΔT_{e}, the region has moved a little further. After the 30th cycle, however, the thermocline thickness has significantly gained, especially, if only small ΔT_{e} are permitted. Looking at the graphs in the third column, in the case with 5 K ΔT_{e}, the thermocline can move only short distances, causing a poor utilization of the storage volume. If the same amount of energy should at given ΔT_{e} be stored within, the bed length of the storage volume would have to be increased. This, in turn, would mean a larger tank, more fluid holdup, more thermal losses and eventually, higher costs. For the simulations, the permitted change in exit temperature ΔT_{e} is varied in the stepping of 10, 20, 40 and 80 K.

During the day, there is a limited time where solar radiation is available. Hence, the charging time ($t'_{\text{e,set}}$), is another important parameter. In the present study, two cases with 8 h and 12 h charging time are investigated. Charging time has mainly an impact on storage size.

The shape of the storage tanks is directly affected by the cross sectional area (A_0). Even though tank diameter and cross sectional area are linked via $A_0 = \frac{\pi}{4}D^2_{\text{stor}}$, the latter parameter has been chosen, since flow speeds inside the packing scale linearly with the cross sectional area but squared with the tank diameter. The length of the storage volume (L_{stor}) is subject to optimization for the emerging combinations of input parameters. In the study, a limitation of the flow length of 200 m has been set. This would be too long for a single tank, but multiple tanks being flown through consecutively could be an option.

Finally, particle diameter (d_{part}) and porosity (ε) are varied. Those parameters are quite convenient, since they almost do not affect the tank design. The particle diameter is varied between 1 mm up to 100 mm. For a mono disperse packing a porosity of 40% can be achieved. By mixing different particle sizes, the porosity can be further reduced [15]. However, in this case pressure loss correlations and thermal models must be adopted accordingly, where the model is not capable for.