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Cite as: AIP Conference Proceedings **2303**, 190022 (2020); https://doi.org/10.1063/5.0029039
Published Online: 11 December 2020

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Slag as an Inventory Material for Heat Storage in a Concentrated Solar Tower Power Plant: Final Project Results of Experimental Studies on Design and Performance of the Thermal Energy Storage

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Abstract. In order to strengthen the competitiveness of concentrated solar power plants, the development of cost-effective storage options is indispensable. For power plants based on air receivers, the technology of direct-flow solid heat storage is an obvious choice. The heat storage inventory used is a significant cost factor for this technology. The use of slag from steel production could significantly improve the competitiveness of this technology. The ReSlag project deals with open questions on the suitability of electric arc furnace slag. This paper presents the final experimental investigations on a pilot scale for the use of sintered electric arc furnace slag in solid heat storage systems. The results of cyclic tests under different operating conditions as well as of standstill tests are presented and successfully compared with simulation results.

INTRODUCTION

One challenge for concentrated solar power (CSP) plants is to guarantee continuous energy output when the sun sets or is blocked by clouds. Thermal energy storage (TES) systems are key components for facing this issue. The state of the art storage system is the molten salt double-tank TES. This heat storage medium implies some disadvantages. The heat transfer fluid (HTF) is on the one hand expensive and on the other hand it demands continuous technical attention to avoid undesired malfunction, such as freezing and degradation. Furthermore, either a special salt receiver or a secondary cycle to be heated by the HTF using a heat exchanger is required, which causes a reduction in thermal efficiency.

A cost-effective, high temperature and efficient performance, single-tank alternative could be provided by the regenerator-type storage based on directly heated solid media. It has a simple setup, is applicable to highest temperatures ($\vartheta > 1000°C$) and has best prospects for a deployment in large installations. A solid media packed bed inventory is a straightforward design option, offering cost-effective solutions [1, 2]. Possible choices for packed bed materials are ceramic pebbles, ceramic saddles or broken natural stone [3]. Due to its classification as waste, a high potential for further cost reduction can be achieved by using slag from steel industry.

The main objective of the European project REslag is the experimental validation of the steel slag as TES material for packed bed systems. In this regard, the final results and conclusions obtained in experimental and simulation studies of a packed bed prototype that implements slag particles as TES inventory and air as HTF will be presented. The design chosen was a vertically installed and axially flowed through TES, as this was identified as the best design in an extensive evaluation phase at the beginning of the project [4]. After detailed investigations regarding the inventory material and the thermo-mechanical behavior [5], here a detailed study of the system

SolarPACES 2019
AIP Conf. Proc. 2303, 190022-1–190022-9; https://doi.org/10.1063/5.0029039
Published by AIP Publishing. 978-0-7354-4037-1/$30.00

performance under different charge, discharge and idle operation conditions is presented. Furthermore, the simulation model [6] for design and up scaled studies is validated by using the obtained experimental results.

METHODOLOGY

The thermal behavior of the slag-based TES was investigated at the HOTREG pilot plant at DLR in Stuttgart, which is described below. The experimental campaign consisted of performing charge, discharge and idle operations under different temperatures up to 700°C, mass flow rates up to 650 kg h^{-1} and cycle times. The aim of the study was the experimental validation of the simulation model [6], and of the construction of insulation and slag pebbles.

Description of DLR Test Facility HOTREG

The DLR test facility HOTREG in Stuttgart, can be seen in Figure 1, is used for the research of design concepts consisting of inner insulations and inventories of high temperature storages for different applications and projects. The facility is based on the regenerator principle with a solid inventory and air or flue gas as a heat transfer fluid. Purpose of HOTREG is the development of design options for high temperature storage units for power plants. The test rig is described briefly below. HOTREG has a high degree of flexibility which is achieved due to:

- interchangeable inner storage tanks,
- variable inventory can be tested,
- pressures, mass flows and temperatures are variable in wide ranges, see below,
- humidity of the inlet air can be changed due to water injection,
- installed measurement instrumentation can be integrated into the process measuring and control technology of the test facility, and
- automatic test mode is possible.
- The main plant data are:
  - 4.3 m^3 inner storage volume.
  - Hot inlet charging 600-830 °C.
  - Cold inlet discharging up to 500 °C.
  - Pressure 1.1 - 11 bar.
  - HTF air 220-720 kg/h.
  - Humidification up to 60 l/h.

FIGURE 1. Test Facility HOTREG at DLR in Stuttgart

Description of the Experimental Tests Performed

Different experiments will be performed that allow to study in detail the performances of the TES unit under real conditions. The experiments comprise different operation conditions such as the startup and shut down, partial charging as well as cyclability tests.

Charging and Discharging Cycle

During a normal day (24 h) the TES is exposed to three different modes, charging, discharging and downtime, as shown in Figure 2. It is assumed that the inventory has a temperature of 20°C when starting the TES charging the first time or after a longer downtime (weeks). At the design day, March the 21st in Huelva (Spain) the charging time is 8 h. This is followed by a 6.5 h discharging time and a 9.5 h downtime of the TES. Afterwards the cycle starts again. These times are for the full scale TES. To get the ones for the pilot plant, an adaption, with the objective to gain thermal equivalent results, was made [6]. The resulting times are given in Table 1.

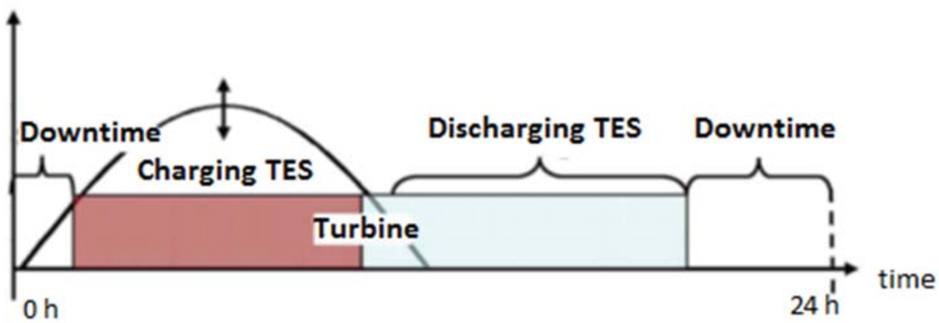

FIGURE 2. Charging – discharging – downtime – cycle.

For a first trial constant charging mass-flow is used. The following trials are performed with parabolic mass-flow according to the curse of the sun.

TABLE 1. Transformed charging and discharging times for pilot.

Date	Full Scale TES			Pilot (HOTREG)	
	Sunshine / h	Charging / h	Discharging / h	Charging / h	Discharging / h
21st March (design point)	12.2	8	6.5	5.2	4.23

Downtime Behavior

The temperature behavior of the TES inventory during different downtimes after the charging cycle is considered. During this period, no mass flows through the inventory.

Insulation Investigation

Four different insulation options are considered:

- Perlite brick (Moler, 64 mm).
- Perlite brick (Moler, 64 mm) + refractory mastic (Mekite, approx. 10 mm).
- Perlite brick (Moler, 64 mm) + steel liner (1.4301, 1 mm).
- Perlite brick (Moler, 64 mm) + super-duty firebrick ULTRA B, 30 mm).

For each insulation option a quarter of the inner containment of HOTREG is prepared (compare Figure 3). After the performed test procedure the different insulation materials were examined for damages caused by the inventory.

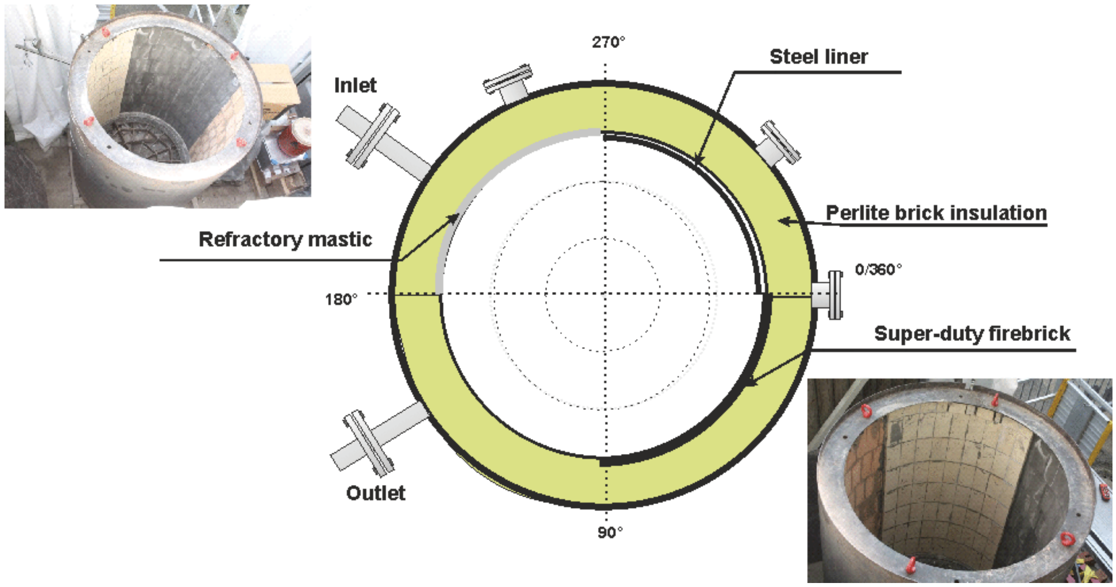

FIGURE 3. Insulation Design Options.

RESULTS

Results of Preliminary Test

In a first step a HOTREG test with the given parameters was done:

TABLE 2. Preliminary test parameter

	Temperature / °C	Mass flow / kg*h^{-1}	Time / h
Charging	700	612	5.2
Discharging	120	677	4.2

Figure 4 shows the temperature variations of the measured temperatures of the preliminary HOTREG test during thermal cycling. Starting at a bed temperature of 120°C, a cyclic charge and discharge with constant parameters given in Table 2 finally leads to a storage operation in cyclic steady state. This can well be seen from the variations of the discharge outlet temperature, having approximated to a settled course after six cycles. Hereinafter, results of the design point (March 21st) test are given and directly compared to results achieved with the developed simulation tool [6].

Results of March 21st Condition Test

The used parameters are given in Table 3. Here a constant discharging mass flow was used, while the charging mass flow behaves like a sine curve. Reason for this is the course of the sun, which belongs to a sine curve. So in Table 3 the average mass flows are given.

TABLE 3. March 21st test parameter

	Temperature / °C	Average mass flow / kg*h^{-1}	Time / h
Charging	700	612	5.20
Discharging	120	677	4.23

Figure 5 shows the measured temperatures over time for the HOTREG test with the 21st of March conditions. The solid lines represent the experimental results. A cyclic charge and discharge, with constant parameters given in Table 3, leads after six cycles to a storage operation in cyclic steady state. This can well be seen from the variations of the discharge outlet temperature, having approximated to a settled course after six cycles.

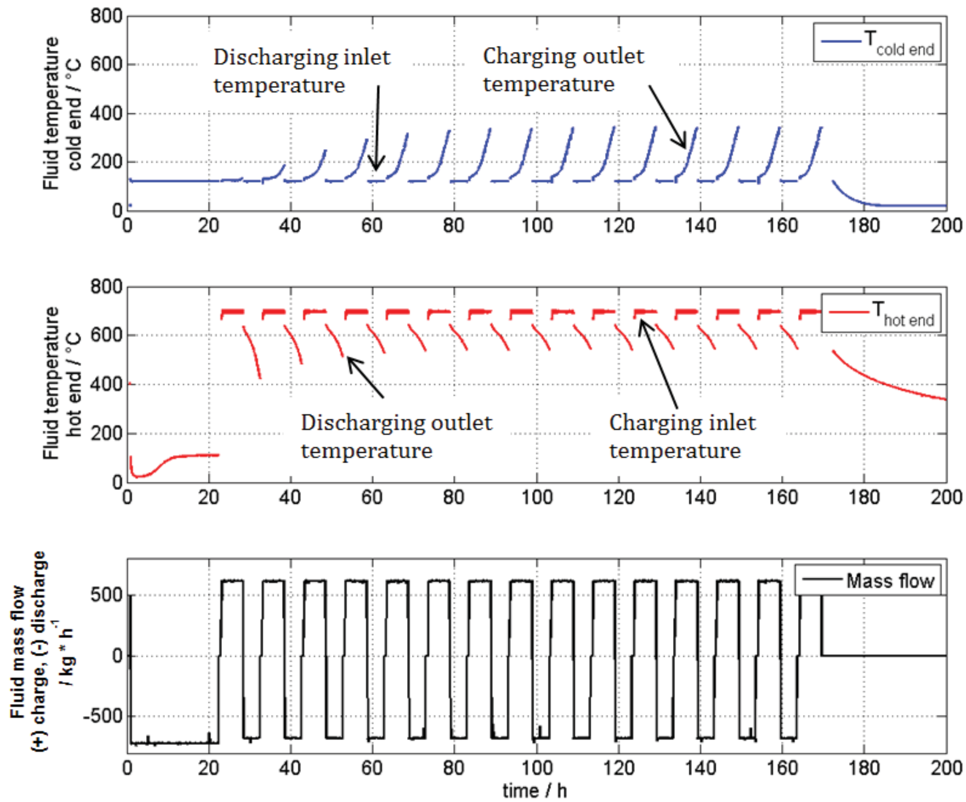

FIGURE 4. Fluid temperature at TES cold end (blue), Fluid temperature at TES hot end (red) and mass flow over charging and discharging (black).

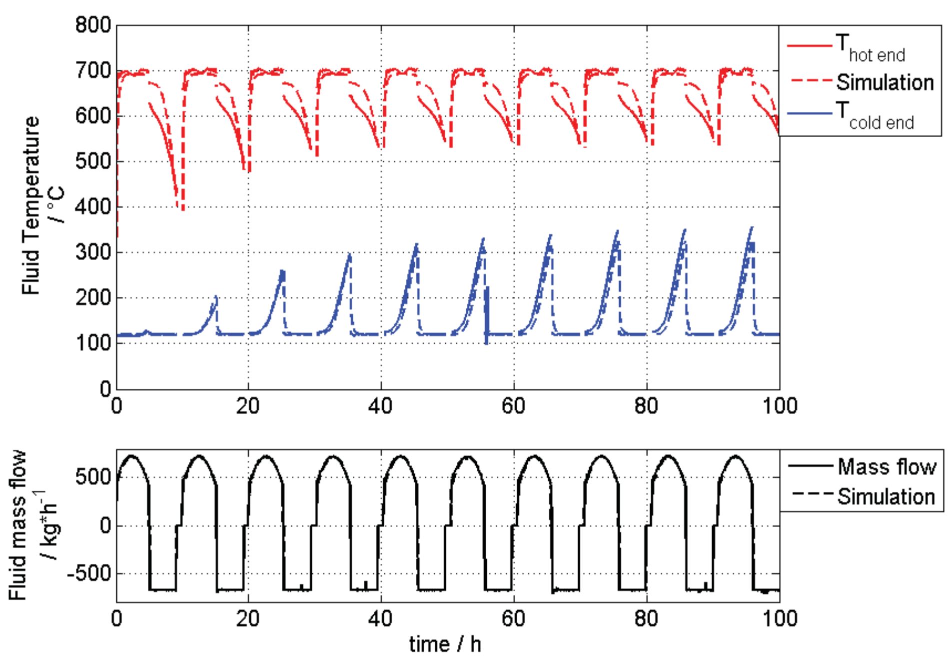

FIGURE 5. 21st of March: Fluid temperature at TES cold end (blue), Fluid temperature at TES hot end (red) and mass flow over charging and discharging (black); solid lines represent the HOTREG results and dashed lines show the simulation model results.

Comparing the experimental results (solid lines) with the results gained by simulation (dashed lines) good accordance can be seen. The maximum deviations of below 10 % are located at the discharging outlet temperature.

Downtime Behavior

The temperature behavior of the inventory of the HOTREG test facility during different downtimes after the charging cycle is considered. The experimental results are compared with results achieved by simulation. In Figure 6 the temperature profile of the inventory is plotted over the storage height. Three different down times are considered (Zero downtime, one day and two days of downtime). By comparing the different experimental downtime results (solid lines), high thermal losses can be seen. After the first day the amount of energy loss is 22 %. This results from the small pilot scale and the thus high surface to volume ratio. The higher losses at the storage ends (0 m and 1.7 m) result from radiation losses at the distributor. Comparing the simulation (dashed lines) results with the experimental ones a good agreement can be seen. The maximum deviation in temperature is below 10 %. Thus the simulation model can be used for full scale design.

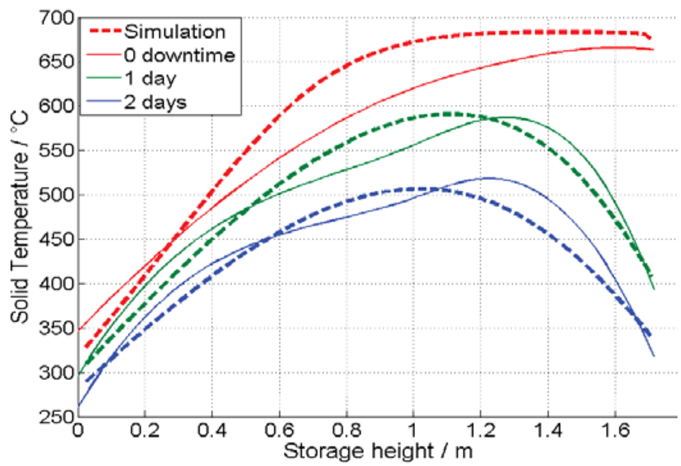

FIGURE 6. Downtime behavior of the fully charged HOTREG (March 21st conditions).

In Figure 7 the downtime behavior of a full scale plant, by using the simulation model, is given. It can be seem, that the thermal losses are, compared to the HOTREG much lower. After 2 days only 1 % of thermal losses are visible. These results confirm the assumption, that a larger TES plant shows lower losses due to the lower surface to volume ratio.

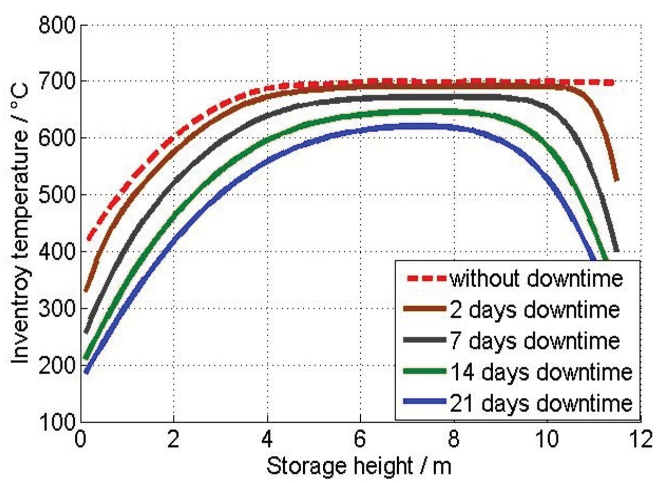

FIGURE 7. Simulated downtime behavior of the full scale plant.

To sum up the experimental results with the test facility HOTREG show a good thermal performance for slag as an inventory material. Furthermore with a maximum deviation of 10 % a good agreement between simulation and experiment is achieved. Deviations can result from the small prototype scale of the test facility and thus higher impact of boundary conditions, as well as from not exactly integrated radiation losses.

Visual Insulation Inspection

The different insulation options were in operation during all HOTREG tests, including preliminary tests. This results in around 200 thermal cycles. Figure 8 and Figure 9 show detailed pictures of the insulation options after the HOTREG tests. On the whole, the tests confirm the results gained within [6], which were received with the compression test rig.

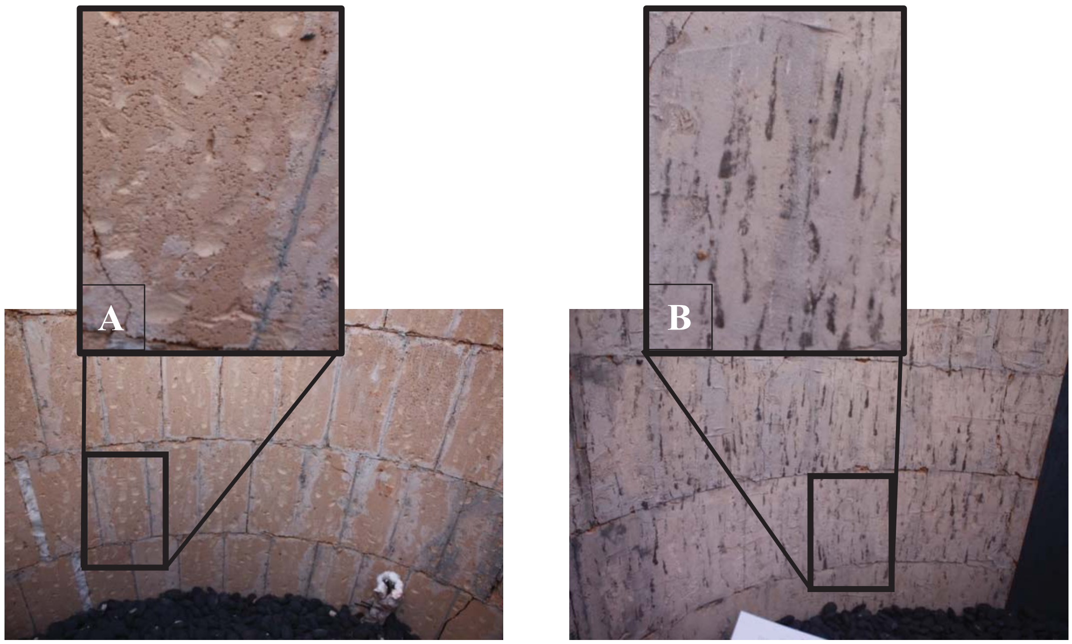

FIGURE 8. Perlite brick insulation (left) and perlite brick insulation with refractory mastic (right) after HOTREG tests.

Figure 8 shows the perlite brick insulation (left) and perlite brick insulation protected with refractory mastic (right). The perlite brick on its own shows minor dents of around one to two millimeters in dept. Furthermore some cracks are visible, which can be seen in the detailed picture (A). Minor dents are also visible in the second insulation option with refractory mastic (B). That does not exactly confirm the results gained with the endurance tests of [6]. There slag particles kept sticking within the mastic. Reason for that could be the thickness difference of the refractory mastic. For the HOTREG test session it was only possible to achieve a mastic thickness of around 3 mm, while the thickness for the compression tests was around 10 mm. So, further investigation for that insulation option is needed.

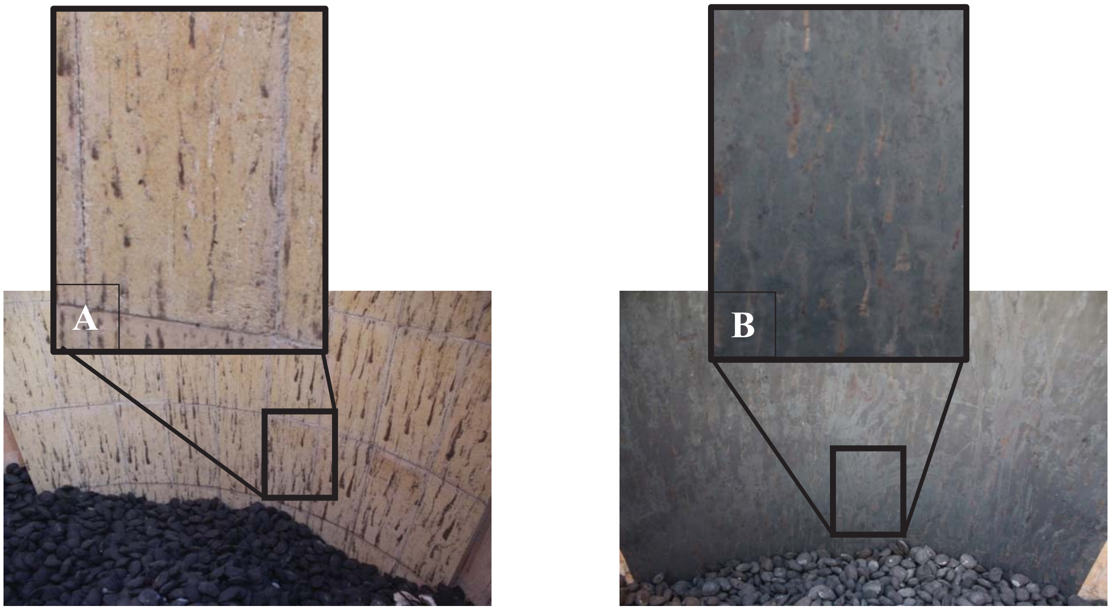

FIGURE 9. Perlite brick insulation protected with super-duty firebricks (left) and perlite brick insulation protected with steel liner (right) after HOTREG tests.

Figure 9 shows the perlite brick insulation protected with super-duty firebricks (left) and perlite brick insulation with steel liner protection. The super-duty firebricks show only little slag scratches and no further damage (A). Scratches are also visible in the steel liner (B). Those results confirm the results received with the endurance tests of [6].

Particle Measurements

During the various pilot plant trials, a measuring probe was used to remove partial streams of the outlet air and cumulatively collect the discharged particles in filter sleeves. Three of these filter sleeve samples were examined. Three fractions were distinguished: Removable coarse particles, filter jacket, and filter cap.

The removable coarse particle mass released from the filters is relatively small. The particle size distribution was measured in each case. The largest proportion of the removable coarse material lies between 5 and 30 µm. In the filter jackets and filer caps the greatest amounts are between 2 and 7 µm.

The microscopic examinations show that dark grey to black iron-containing particles are present in all three filter samples. Some of these particles are magnetic (magnetites) and are strung together like a chain. Other ferrous particles show platy forms with brown oxidation traces in the form of iron oxide hydroxides or iron hydroxides. In addition, light-colored, transparent and glass-like solidified particles are occasionally found in different forms of training. Depending on the type of metal and its mass fraction, these have different reddish-brownish to greenish colors. In addition, fibrous, green-colored particles can be detected, some of which are large grain sizes from 1 to 2 mm.

CONCLUSIONS

Overall the investigations carried out in the project REslag clearly indicates the thermal und mechanical suitability of a slag-based packed bed for the use as inventory material for regenerator-type TES in CSP plants with air as HTF. The cyclic thermal tests confirm both the validity of the thermal models and the design of the lead concept. Viable protection measures were elaborated for inner insulation. Remaining uncertainties must be further reduced after the project, such as long-term stability, dust generation, and exact thermomechanical behavior of the sintered pebbles.

ACKNOWLEDGMENTS

This work has been supported by the H2020-WASTE-2014-two-stage (WASTE-1-2014) program through the Project 642067-RESLAG–IA (http://www.reslag.eu/).

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