# Slag as an inventory material for heat storage in a concentrated solar tower power plant: Experimental studies on design and performance of the thermal energy storage

Cite as: AIP Conference Proceedings **2126**, 200022 (2019); https://doi.org/10.1063/1.5117737
Published Online: 26 July 2019

Jürgen Haunstetter, Michael Krüger, and Stefan Zunft

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

Jürgen Haunstetter[1, a)], Michael Krüger[1, b)], Stefan Zunft[1, c)]

[1]*German Aerospace Center (DLR), Institute of Engineering Thermodynamics, Pfaffenwaldring 38-40, D-70569 Stuttgart, Germany*

[a)]Corresponding author: Juergen.Haunstetter@dlr.de
[b)]Michael.Krueger@dlr.de
[c)]Stefan.Zunft@dlr.de

**Abstract.** Thermal energy storage systems are essential for concentrated solar power plants to guarantee continuous energy output. Currently used molten salt technologies are very expensive and demand continues technical attention. An option for cost reduction and efficiency increase is to use regenerator-type energy storages. Further cost reduction can be achieved by using the waste metallurgical slag from electric arc furnace as an inventory material for the thermal energy storage. So far only a few studies have been carried out regarding the use of EAF slag as TES inventory material. Nonetheless, there are still fundamental questions about this low-cost material and storage design to be clarified. The European project RESlag deals with those questions. In this paper, experimental design and performance studies of slag-based thermal energy storage are carried out. The basic methodology for simulation model set up is declared and a lead design is identified. The set-up of the used test facility, called HOTREG, is described and the measurement arrangement is explained in detail. Furthermore, experimental results of the thermal behavior of the HOTREG with slag as heat storage inventory are presented and compared with results of an appropriate simulation model. Here, the comparison yielded an agreement of over 90 %.

## INTRODUCTION

Thermal energy storage (TES) systems are key components of concentrated solar power (CSP) plants to guarantee continuous energy output. However, the currently used molten salt technologies show different drawbacks like freezing, decomposition and other issues regarding the heat transfer fluid (HTF). To avoid those undesired malfunctions, continuous technical attention is needed, which is related with high costs.

Due to its free availability and non-hazardous characteristic, air is a cost-effective HTF alternative. Based on its high possible operation temperature, air also has a particularly promising potential for high solar-to-electric efficiency. Here, regenerator-type TES systems with a packed bed inventory are 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 [8]. Due to its classification as waste, there is a high potential for further cost reduction by using slag from steel industry.

However, for a successful market introduction of this technology, efficient and up-scalable solutions for the TES are a prerequisite. Regenerator storages are well suited to the needs, but need further research regarding the implementation in large installations in combination with slag pebbles as inventory. The EU project RESlag is dedicated to answer these open questions.

*SolarPACES 2018*
AIP Conf. Proc. 2126, 200022-1–200022-9; https://doi.org/10.1063/1.5117737
Published by AIP Publishing. 978-0-7354-1866-0/$30.00

## STATE OF THE ART OF TES IN CSP

In CSP plants, molten salt technologies have been extensively deployed for storage of thermal energy. An example among many is the Solana power plant with 280 $MW_{el}$ and a storage system able to supply full power for six hours. [2]

Less advanced is the technology of regenerator-type storage. The prospect of this technology is the potential for higher efficiency and lower costs, due to its applicability to high temperatures ($\vartheta$ > 1000°C), its simple one tank setup and the free availability of the HTF (air) [3, 4]. At present, the world's only TES plant based on this technology is integrated into the Solar Power Tower Jülich in Germany, see FIGURE 1. This experimental central receiver plant was put into operation in 2009. The construction and operation of the plant were accompanied by a research program with the objective to cover remaining uncertainties of design and operation and to further promote the development of the technology towards a commercial deployment. As a part of this work program also heat storage operation and design were addressed [6].

**FIGURE 1.** Solar power tower Jülich (Germany)

The plant uses an open volumetric receiver technology developed at DLR. In its primary cycle, air at atmospheric pressure is heated up to temperatures of about 700 °C. This solar heat then powers a steam generator, producing steam at 100 bars and 500 °C and powering a 1.5 $MW_{el}$ turbine-generator. Parallel to the steam generator and receiver, a thermal energy storage is integrated into the power cycle, see FIGURE 2, which is implemented as air-cooled regenerator storage [7].

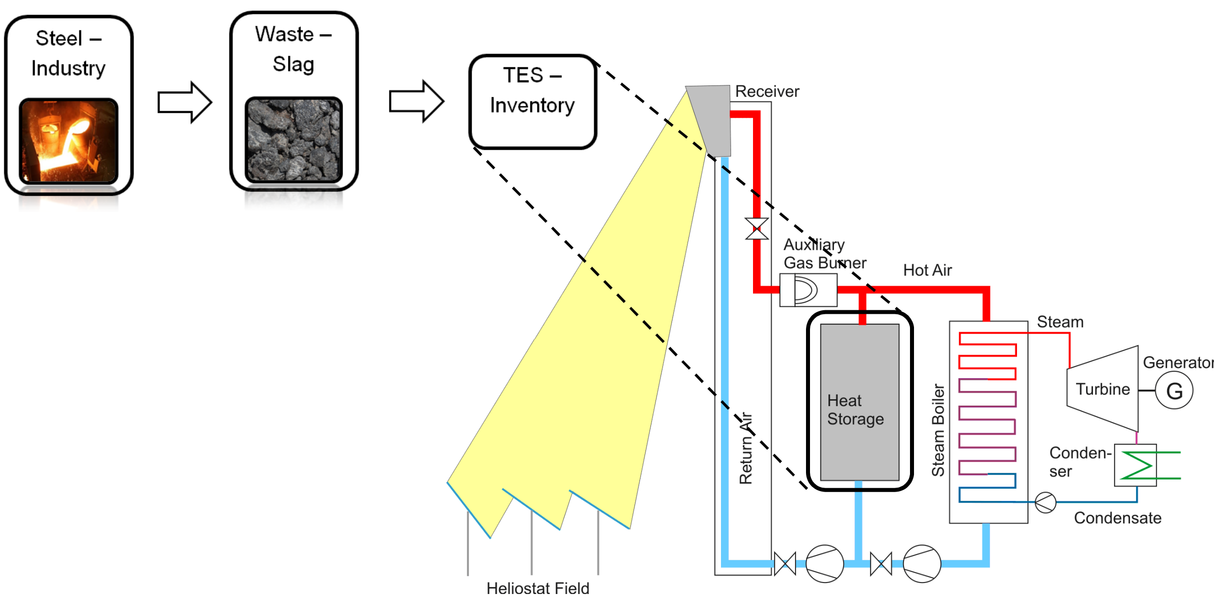



**FIGURE 2.** Flow sheet of solar power tower Jülich and slag reuse as TES inventory in CSP plants

Regenerator-type storages allow operating temperatures of 1000 °C and above by using solid storage material such as commercial available bricks or beds of smaller particles made of oxide ceramic material [8]. Recent work [9], [10], [11] and [12] is focused on the investigation of low-cost alternative inventory materials such as low temperature fired clay bricks and magmatic natural stones.

An alternative to this is the revaluation of slag from electric arc furnace (EAF), which is a low-cost inventory solution due to its classification as waste. So far only a few studies have been carried out regarding the use of EAF slag as TES inventory material. Calvet et al. investigated the thermochemical stability and thermophysical properties of EAF slag [15]. Nonetheless, there are still fundamental questions about the material and TES design to be clarified. These questions are addressed by the European project REslag. The main objective of the project is to make an effective valorization of the steel slag and reuse it as a feedstock for four innovative applications – one of them are thermal energy storage systems in CSP applications [13].

In this paper, experimental design and performance studies of slag-based thermal energy storage are carried out. The basic methodology of the TES simulation model is presented and the previously determined lead concept is used as a basis for experimental investigations at the test rig. Finally, first experimental results are compared to the simulation model.

## DESIGN OF SLAG-BASED TES

Initially, different possible slag based TES designs were developed, calculated and evaluated by the application of established management tools. For this reason, simplified continuous solid phase models were set up for a first estimation of the thermal design and TES dimensions. Details on the basic model can be found in [5] and [14]. The boundary conditions applied for the calculations are based on the specifications of a 150 MWel CSP plant as well as material properties of slag (TABLE 1).

**TABLE 1**. Full scale air CSP plant specifications (a) and used slag parameter (b)

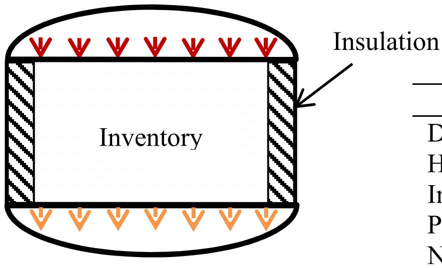
(a)

| Description | Characterization |
|---|---|
| Rated net power output of CSP plant | 150 $MW_{el}$ |
| TES capacity | 6.5 hours (2.21 GWh) |
| TES inlet temperature while charging | 700 °C |
| TES inlet temperature while discharging | 120 °C |
| Max. temperature drop at TES outlet while discharging | 60 °C |
| Max. pressure loss through the TES | 100 mbar |
| Discharging mass flow | 780 kg $s^{-1}$ |
| Max. charging mass flow through TES | 1080 kg $s^{-1}$ |
| Mean charging mass flow through TES | 706 kg $s^{-1}$ |
| Charging duration | 8 h |

(b)

| Slag properties | Value |
|---|---|
| Density | 3430 kg $m^3$ |
| Thermal conductivity | 1.43 W (m K) $^{-1}$ |
| Specific heat capacity | 0.933 kJ (kg K)$^{-1}$ |

Afterwards, in order to identify a lead concept, an aptitude and risk analysis based on the quality function deployment method, was performed. As a result, the vertical storage design with axial flow direction showed the highest aptitude value and the lowest risk value. Therefore, this TES design was taken as the lead concept and is investigated in detail in further research (FIGURE 3).




| Parameter | Value |
|---|---|
| Diameter | 16.7 m |
| Height | 11.6 m |
| Inventory mass | 31375 t |
| Particle diameter | 0.035 m |
| Number of TES container | 6 |

**FIGURE 3**. Lead concept sketch and its specifications

## EFFICIENCY AND PERFORMANCE ANALYSIS OF LEAD CONCEPT

An efficiency analysis – storage capacity, thermal losses and pressure drop – as well as an analysis of the dynamic behavior was used to refine the lead concept.

The simulation models for the dynamic behavior analysis of the TES are set up according to the continuous solid phase model described by Ismail [14]. Besides the assumption of a solid continuous medium, it is also assumed that the heat transfer in the bed is by conduction. Furthermore the radiation heat transfer mechanism and the radial heat exchange are neglected. The applied energy differential equations are listed below.

$$\text{Fluid:} \quad \varepsilon\rho_f c_{pf}\left(\frac{d\bar{T}}{dt} + v_\infty \frac{d\bar{T}}{d\bar{x}}\right) = \underbrace{k_{fx}\frac{d^2\bar{T}}{d\bar{x}^2}}_{\text{Conduction}} + \underbrace{h_{sf}a_p(\bar{\theta} - \bar{T})}_{\text{Convection}} - \underbrace{U_w a_w(\bar{T} - \bar{T}_0)}_{\text{Heat loss}} \tag{1}$$

$$\text{Solid:} \quad (1-\varepsilon)\rho_s c_{ps}\frac{d\bar{\theta}}{dt} = k_{sx}\frac{d^2\bar{\theta}}{d\bar{x}^2} + h_{sf}a_p(\bar{T} - \bar{\theta}) \tag{2}$$

During a normal day (24 h) the TES is exposed to three different modes, charging, discharging and downtime, as shown in FIGURE 4. It is assumed that the initial temperature of the TES is 20°C. 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. Furthermore, it is assumed that the discharging starts in full load after the charging period, not in partial load.

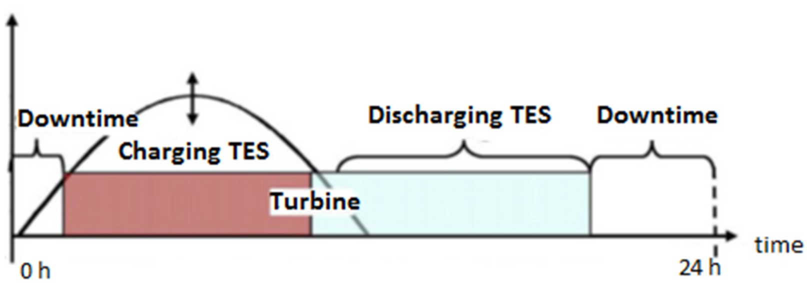
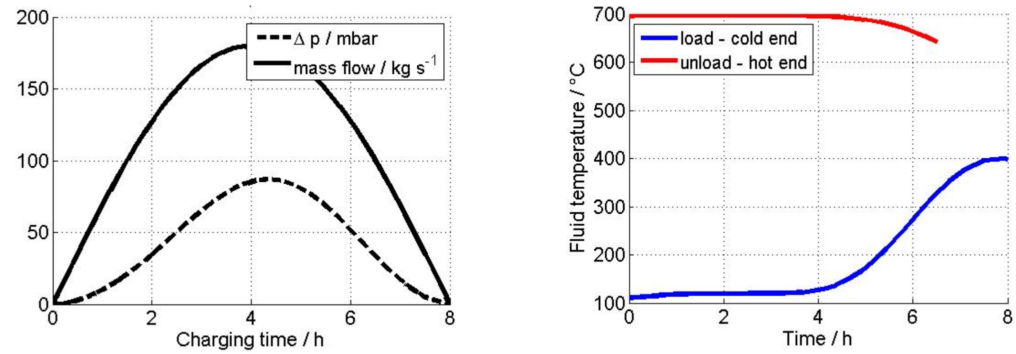



**FIGURE 4.** Charging – Discharging – Downtime – Cycle

FIGURE 5 illustrates the model results for the design point of the full scale lead concept in steady state conditions. On the right hand side, the fluid outlet temperatures over time during charging and discharging are shown. It can be seen, that the maximum temperature drop of 60°C can be reached. The decreasing slope of the loading curve at around 6.5 h is caused by the decreasing mass flow.

The mass flow and pressure drop change during charging are displayed on the left hand side. The charging depends on the solar altitude, therefore the mass flow changes according to a sinus curve and the pressure drop in dependence to the mass flow. This results in a maximum pressure drop of 87 mbar when the sun is at its zenith.




(a) (b)

**FIGURE 5.** Lead concept: mass flow (a), pressure drop (a) and fluid temperature (b) results

FIGURE 6 shows the transient response of the TES over 16 days (a constant sunshine period and TES use is assumed). The red curve represents the fluid temperature of TES at the hot end section, while the blue one represents the cold end, respectively. By looking at the peaks of the cold end outlet temperature, it can be assumed that around 8 days no significant temperature changes take place anymore. This means that a steady state condition is reached after 8 days.

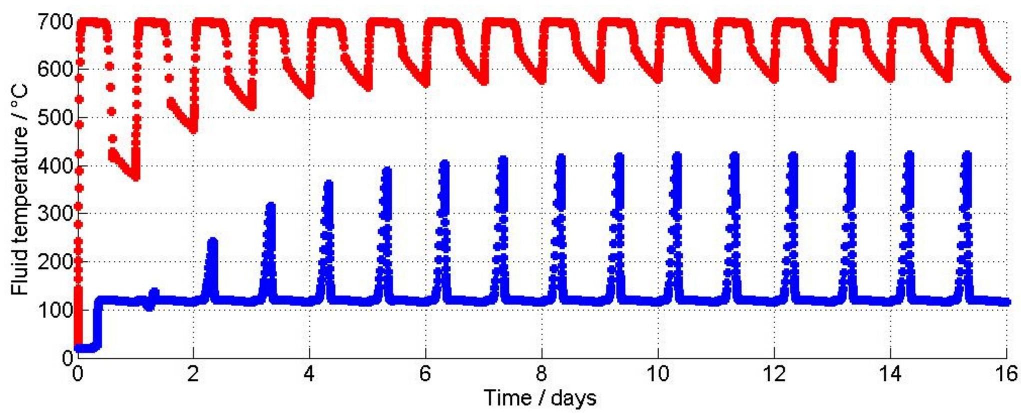



**FIGURE 6.** Transient response over 16 days; red: hot end; blue: cold end

Results gained with the simulation model indicate the suitability of slag as inventory material for TES. To confirm the results, the simulation model needs to be validated. For this purpose a previously constructed experimental test rig is used. In addition, further investigations like the thermal stability of the slag, can be carried out.

## EXPERIMENTAL SET UP

For experimental investigation of inventories and insulations of high temperature energy storages the DLR test facility "HOTREG" in Stuttgart, which can be seen in FIGURE 7 (a), is used. The facility is based on the regenerator principle with a solid inventory and air or flue gas as a heat transfer fluid. One purpose of the conducted experiments at HOTREG is the development of design options for high temperature storage units for power plants.

(a) (b)

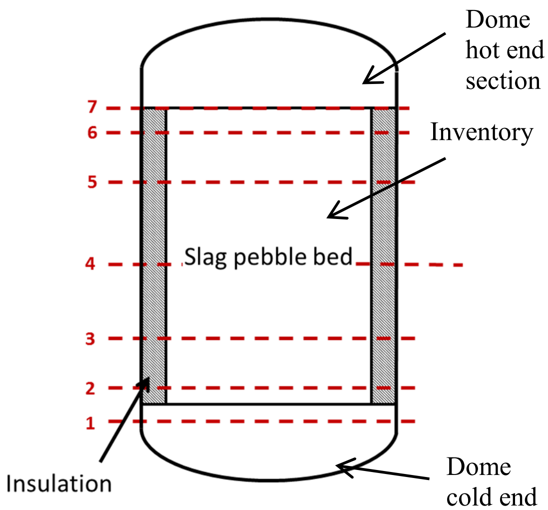
**FIGURE 7.** HOTREG test facility at DLR in Stuttgart (a) and test setup for slag-based TES (b)

The main structural components are an air compressor, compressed air heater, regenerative storage tank, cooling circuit and the central control unit. The air compressor is a speed-controlled screw compressor with an engine nominal capacity of 90 kW. It is able to provide continuous air flows between 220 kg $h^{-1}$ and 720 kg $h^{-1}$ at pressures between 1.1 bar and 11 bar at the compressed air heater inlet. The compressed air heater is an indirectly heated, double-flue heater in cylindrical, horizontal design with helical-shaped single line plain tube heat exchanger surfaces, separated for “charging” and “discharging”. The central part for storing heat is the regenerative storage tank, which is illustrated in FIGURE 7 (a). It consists of a pressure vessel with inside insulation and water cooling at the outside (double shell). For experiments the inner storage tank can be changed, to test different inventory materials, here slag pellets (FIGURE 7 (b)). The main technical details of the HOTREG are listed in TABLE 2.

**TABLE 2.** Basic HOTREG data

| Parameter | Value |
|---|---|
| Inner storage volume | 4.3 $m^3$ |
| Max. diameter of inventory | 1.7 m |
| Max. height of inventory | 1.9 m |
| Mass flow | 220 – 720 kg $h^{-1}$ |
| Operating pressures | 1.1 – 11 bar |
| Storage inlet temperature, charging | 600 – 800 °C |
| Storage outlet temperature, charging | Up to 500 °C |
| Storage inlet temperature, discharging | 20 – 400 °C |
| Storage outlet temperature, discharging | Up to 800 °C |
| Humidification | Up to 60 l $h^{-1}$ |

For the actual test campaign, the inner storage tank is equipped with an inner insulation and is filled with 4.85 tons of slag pellets (compare FIGURE 7 (b)). A total amount of 35 “Type K” thermocouples (TC) are installed inside of and near to the packed bed. The storage height is separated into seven levels like illustrated in FIGURE 8. Level 1 and 7 are near the inventory and Level 2 to 6 are located within the storage material. Every level is equipped with five TCs for inventory temperature recording, except Level 3 and Level 5. Here four TCs are placed within the insulation. The TCs of each level are arranged in a circle, with a diameter of 1000 mm, inside the inventory. For later evaluation mean level temperatures are used.




(a)

| Level | Height / mm | Thermocouples |
|---|---|---|
| 7 | 1715 | 5 |
| 6 | 1470 | 5 |
| 5 | 1225 | 5 + 4 in insulation |
| 4 | 980 | 5 |
| 3 | 245 | 5 + 4 in insulation |
| 2 | 0 | 5 |
| 1 | -100 | 5 |

(b)

**FIGURE 8.** Schematic drawing of the TES (a) with different levels of thermocouple placement (b)

## RESULTS

Since the measurement campaign is still ongoing, one experiment is evaluated as an example and its results are discussed and compared with simulation results. The temperature and mass flow parameters used for the HOTREG experiment were determined by adaption of the full scale design to the pilot scale. Resulting test parameters are given in TABLE 3.

**TABLE 3.** Test parameter

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

FIGURE 9 illustrates the fluid temperature courses of the hot and cold end section and the mass flow of the HOTREG test during thermal cycling. In addition, the simulation results are plotted with dotted lines. The initial experimental bed temperature is 120°C, which is followed by cyclic charging and discharging with constant parameters (TABLE 3). This finally leads to a storage operation in cyclic steady state, which can be observed from the variations of the discharge outlet temperature (red courses), having approximated to a settled course after six cycles. The temperature gap of around 50 °C between the charging inlet and discharging outlet temperature (red courses) is a result of from the small prototype scale of the HOTREG test facility, which equates to higher thermal losses.

There is a good agreement between simulation results (dotted lines) and experimental results (solid lines). The outlet temperature while charging (blue) is within the range of 10 °C. The course of the discharging outlet temperature over the time shows a maximum deviation of 60 °C, which corresponds to accuracy levels of over 90 %. The deviation is a result of the small prototype scale of the HOTREG test facility and thus, higher impact of boundary effects such as plant-specific radiation losses. Those boundary effects are actually not integrated in the simulation model, yet.

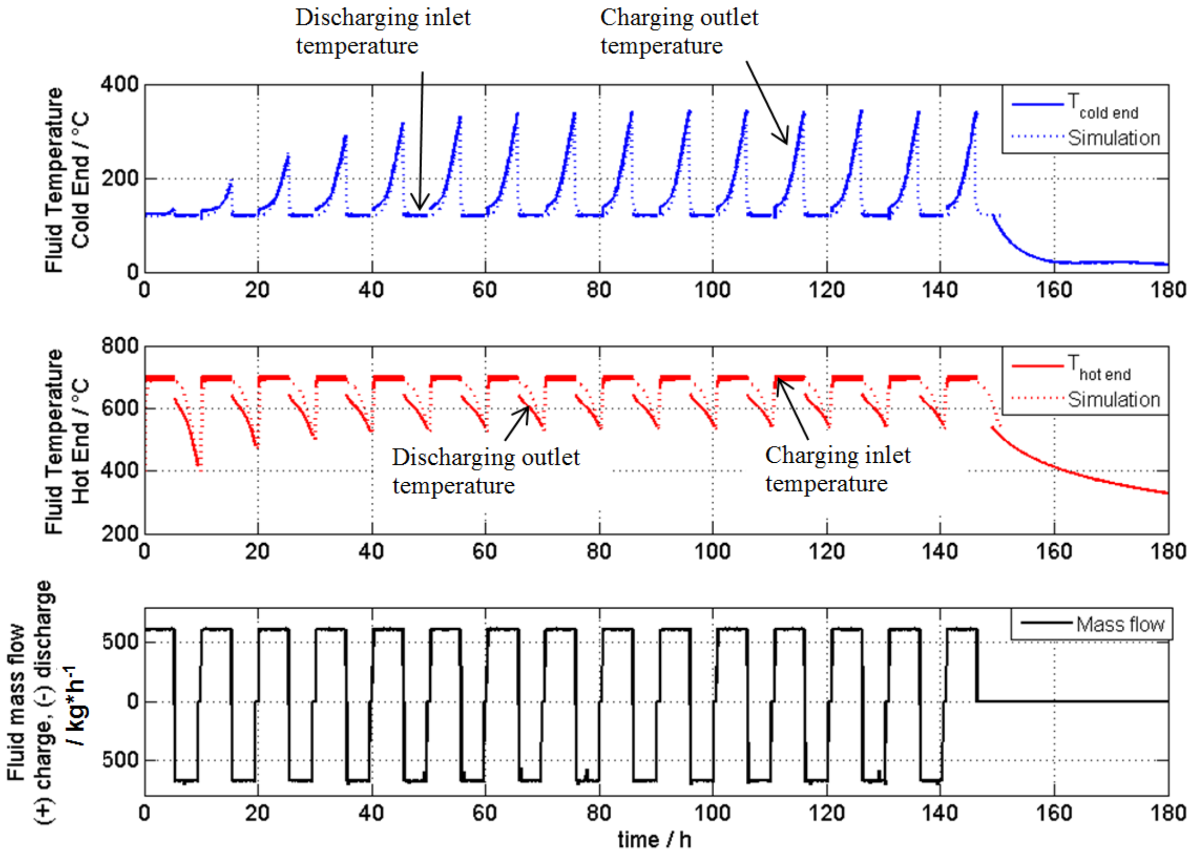



**FIGURE 9.** Fluid temperature at TES cold end (blue), Fluid temperature at TES hot end (red) and mass flow over charging and discharging (black)

## CONCLUSIONS

First results of the test campaign at the HOTREG test facility at DLR in Stuttgart confirm the suitability of the slag pellets developed in the RESLAG project as an inventory material for CSP power plants with an open volumetric receiver. The simulation results are in good agreement with the measurement results. An accuracy of over 90 % could be achieved. The detected deviations are a result of simplified model assumptions. Additionally, the prototype scale of HOTREG lead to higher impact of radiation losses. However, in the further course of the project further improvement and extension of the developed simulation tools are intended and ongoing experiments with the HOTREG will be evaluated.

## ACKNOWLEDGMENTS

This project has received funding from the European Union’s Horizon 2020 research and innovation program under grant agreement No 642067.

## REFERENCES

1. R. Pitz-Paal, “Solar Energy - Concentrating Solar Power,” in Future Energy, New York, Elsevier Science, 2014, pp. 405-431.
2. European Association for Storage of Energy (EASE); European Energy Research Alliance (EERA), “European Energy Storage Technology Development Roadmap - 2017 Update,” 2017.

3. Haeger, M. et al.: Phoebus Technology Program Solar Air Receiver (TSA). "Operational Experiences with the Experimental Set-Up of a 2.5 MWth Volumetric Air Receiver (TSA) at the Plataforma Solar de Almería". PSA-TR02/94, 1994.
4. Fricker, H. W., "Regenerative thermal storage in atmospheric air system solar power plants", Energy, vol. 29, pp. 871–881 2004.
5. Dreißigacker, V. et al., "Thermo-mechanical analysis of packed beds for large-scale storage of high temperature heat", Heat Mass Transfer, vol. 46, pp. 1199-1207, 2010.
6. S. Zunft, M. Hänel, M. Krüger, V. Dreißigacker, F. Göhring and E. Wahl, "Jülich Solar Power Tower - Experimental Evaluation of the Storage Subsystem and Performance Calculation," Journal of Solar Energy Engineering, vol. 133, no. 3, pp. 1019-1023, 2011.
7. S. Zunft, M. Hänel, M. Krüger and V. Dreißigacker, "A design study for regenerator-type heat storage in solar tower plants - Results and conclusions of the HOTSPOT project," Energy Procedia, vol. 49, pp. 1088-1096, 2014.
8. D. Laing und S. Zunft, „Using concrete and other solid storage media in thermal energy storage (TES) systems", in Advances in Thermal Energy Storage Systems: Methods and Applications, Cambridge, Woodhead Publishing, pp. 65-86, 2015.
9. K. Stahl, P. Moser, R. Marquardt, M. Siebert, S. Kesser, F. Maier, M. Krüger, S. Zunft, V. Dreißigacker and J. Hahn, "Flexibilisierung von Gas- und Dampfturbinenkraftwerken durch den Einsatz von Hochtemperatur-Wärmespeichern (FleGs): F&E Vorhaben zur Vorbereitung von Hochtemperatur-Wärmespeichern und deren Integration in den Gas- und Dampfturbinenprozess", 2013.
10. K. Stahl, S. Zunft, S. Kessler and M. Siebert, "Flexibilisierung von GuD-Kraftwerken durch den Einsatz von Hochtemperatur-Wärmespeichern", in VDI-Konferenz "GuD-Kraftwerke im dynamischen Netzbetrieb", Köln, 2011.
11. S. Zunft and S. Freund, "Large-scale Electricity Storage with Adiabatic CAES - the ADELE-ING project", in Energy Storage Global Conference, Paris, 2014.
12. S. Zunft, "ADELE-ING: Engineering-Vorhaben für die Errichtung der ersten Demonstrationsanlage zur adiabaten Druckluftspeichertechnik," 2017.
13. "RESLAG," [Online]. Available: http://www.reslag.eu. [Accessed 18 05 2018].
14. Ismail, K. and Stuginsky, R., "A parametric study on possible fixed bed models for pcm and sensible heat storage", Appl Therm Eng, vol. 19, pp. 757-788, 1999.
15. N. Calvet, G. Dejean, L. Unamunzaga, X. Py, "Waste from Metallurgic Industry: A Sustainable High-Temperature Thermal Energy Storage Material for Concentrated Solar Power," ASME 2013 7th International Conference on Energy Sustainability, No. ES2013-18333, doi:10.1115/ES2013-18333.