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Experimental Testing Of a 400 Kwh Steel Slag-Based Thermal Energy Storage Prototype For Industrial Waste Heat Recovery Applications

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Abstract – There is a clear need to develop cost-effective thermal energy storage systems to improve industrial energy efficiency since great amounts of energy is lost as waste heat. In this paper, a cost-effective 400 kWh thermal energy storage prototype for waste heat recovery at high temperature is tested over different charging and discharging conditions. The technology studied is based on the use of steel slag as thermal energy storage material and air as heat transfer fluid, in a packed bed reactor of 1 m^3. Since the steel slag is a by-product of the steelmaking industry its cost is almost negligible, whilst its thermomechanical properties make it very attractive to store heat. The aim of the testing studies is to gather information regarding the heat exchange efficiency between the heat transfer fluid and the slag in different temperature levels, reproducing common industrial off-gas waste heat release. Finally, with these results a technoeconomic calculation approach is provided in the frame of a real waste heat recovery plant in the steelmaking industry, which confirms this technology as a very promising candidate for waste heat recovery solutions.

Keywords**:** thermal energy storage; waste heat recovery; steel slag

1. Introduction

The global warming development are demanding serious actions and process industry may significantly help to reduce its negative effects, since it is responsible of more than one third of the total energy consumption worldwide. Furthermore, the slight growth of the energy intensive industries (EIIs) is fastening the trend. EIIs are those industries with the largest carbon footprint and are often represented by food, pulp and paper, basic chemicals, refining, iron and steel, nonferrous metals (mainly aluminium), and non-metallic minerals (mainly cement). The main type of energy end-use among these industries is heat, accounting for 50% of the total worldwide heat consumption [1], which represents by far the largest energy end-use type.

On the supply side, nowadays heat production means are still based on fossil fuels, but inherent to the industrial processes, somewhere between 20 to 50% of the energy input is lost as waste heat. Hot exhaust gases, cooling water streams or free heat losses from incandescent surfaces are widespread examples of a waste heat scenario where, burning fossil fuels still became cheaper than recovering and reusing the excess of the so-called waste heat. Nevertheless, the rules of the game are changing fast, primarily represented by the progress towards phasing out fossil fuels subsidies, whilst energy efficiency subsidies keep increasing. The contribution of these policies, in addition to the technology development, are reaching to a point where the return of investment of a solution to recover and reuse waste heat may claim the interest of the financial managers, since it is becoming a reliable investment.

Nevertheless, in a similar scenario of renewable energy sources, the industrial waste heat sources can not be managed in terms of waste heat recovery interest, since respond to production goals. Therefore, it often becomes highly difficult to reuse the waste heat, since the possibilities to find a heat sink that matches the waste heat disposal is scarce. In this context, energy storage is conceived to provide a solution, provided that the investment cost competes with the prize of fossil fuels.

During last years an intensive research work has been developed to evaluate low-cost thermal energy storage systems for high temperature, mainly based on the so-called packed bed or thermocline technology. This technology is based on using particles of a solid material, contained in a vessel in a random arrangement, through which a gas flows, exchanging the heat with the solid particles. The research has been focused mainly in using Al_2O_3 [2] [3], ZrO_2 [4], in a reduced scale prototypes (< 100 kWh), achieving efficiencies up to 80%. Considering these results, our research team focused on studying the viability of using steel slag as filler material, since it is a by-product of the steel industry and therefore, its cost is negligible. First studies identified the attractive thermomechanical properties of the steel slag to be used as a filler material [5] and subsequently, a 400 kWh prototype was built and used to validate a thermal model [6]. The following step is presented in this paper, where a comprehensive testing campaign of the 400 kWh prototype over multiple charging and discharging operations has been carried out, aiming to identify the efficiency of the processes and assess the techno economic viability of using steel slag in a packed bed configuration for thermal energy storage.

2. Experimental facility

The testing infrastructure is based on an open hot air system capable of heating air up to 800°C for flow rates from 180 kg/h and up to 360 kg/h. To meet these conditions, the installation is equipped with two electric heaters that provide a power of up to 100 kWt, two fans to move the air, an exhaust stack and two three-way valves for circuit management (Figure 1). The use of these valves allows the charging and discharging processes of the storage system to be tested, since they are carried out in an opposite direction, as well as offering the possibility of bypassing the testing object.

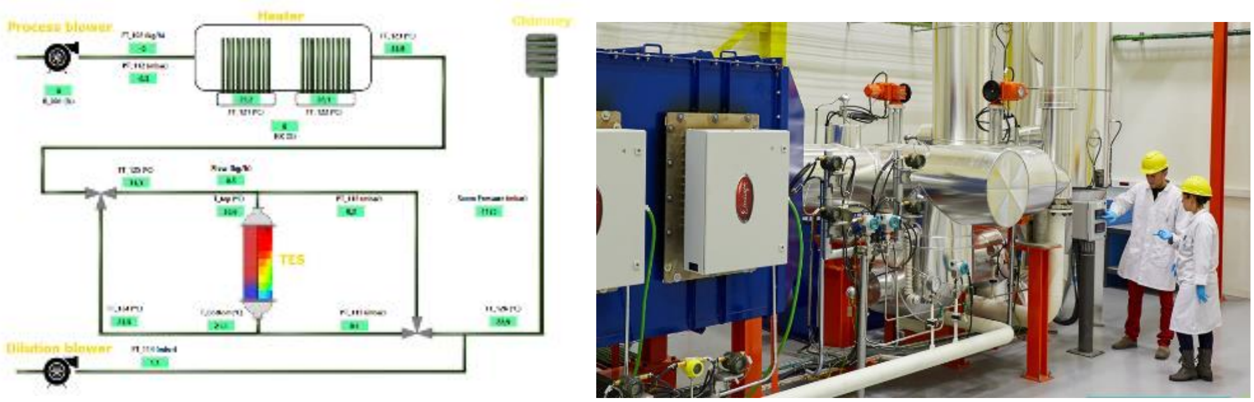

Fig. 1: Hot air testing infrastructure: components scheme and picture of the hydraulic hot air installation

The facility is prepared to insert any type of testing object in the hydraulic system. It is controlled by remote using Labview and the results are recorded in real time. The objective of the infrastructure is to evaluate the performance of the thermal energy storage system during charging and discharging operations. The testing scale allows for the execution of fast and flexible testing campaigns, whilst ensuring reliable outputs to assess the scalability of the solution to a real industrial scale.

3. Material characterization and prototype design

The steel slag particles used as energy storage material were previously subjected to a mechanical treatment to smooth the sharp profiles and select the most stable particles, since some of them broke during this process. The treatment carried out consisted of placing the particles in a concrete mixer for 24 hours. Subsequently, the particles were sieved and particles out of an average size between 1 to 2 cm were discarded (Figure 3a). The thermophysical properties of the slag were obtained in a previous work [5] and are indicated in Figure 3b.

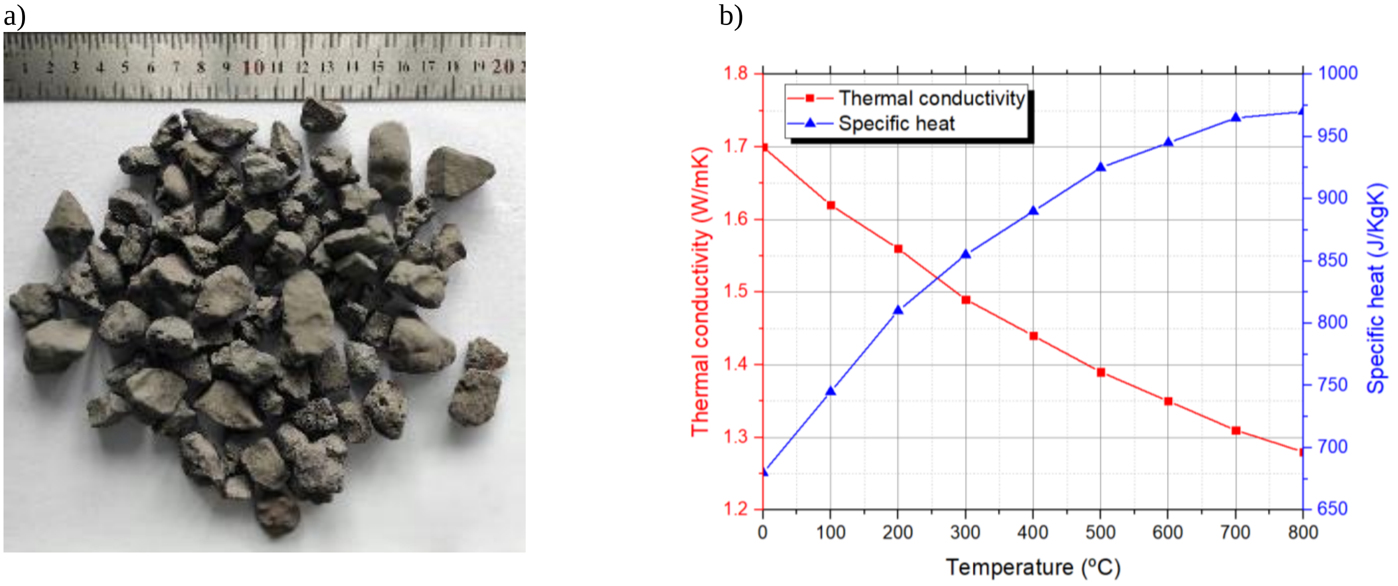
a)
b)

Fig. 3. Slag used in the TES prototype: a) picture of the slag selected particles and b) main thermal properties of the steel slag

The heat storage system to be tested consists of a cylindrical tank with a radius of 43 cm and a height of 173 cm, giving it a volume of 1 m^3 (Fig. 4). In order to get a uniform distribution of the air flow into the tank it is essential to pay attention to the design of the inlets of the tank [7]. In our case, the design consisted of a conical diffusor, which performance was checked by CFD simulation tools (Fig. 4). The steel slag particles introduced into the tank were previously weighted, reaching a total weight of 980 kg.

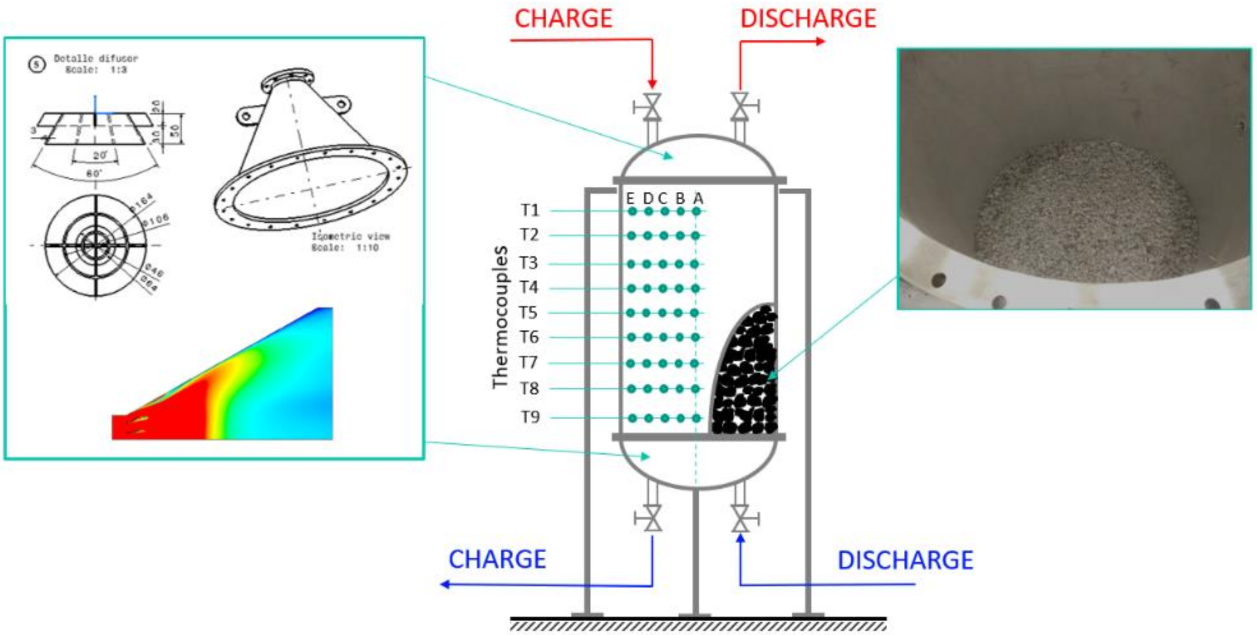

Fig. 4. Picture of the TES tank prototype

4. Experimental results

Several experimental conditions were tested in the prototype. The objective of such tests is the evaluation of the steel slag response under different discharging conditions. The investigated parameters are the initial slag temperature (charge conditions), the discharging temperature and/or the exploited temperature range (ΔT). The conditions of the performed experiments are included in Table 1. It can be noted that all experiments were repeated at least twice to ensure reproducibility of the obtained results.

Table 1: Caption for table goes at the top.

Experiment number	Charging temperature (°C)	Discharging temperature (°C)	Air mass flow (kg/h)
1	500	Room	300
2	400	Room	300
3	200	Room	300
4	400	200	300
5	500	300	300

Maximum slag charging temperature was limited to 500°C since this is the maximum average temperature of most furnace exhaust gases after recovering waste heat through common recuperators. Furthermore, in addition to use air at room temperature, which represents the most probable and easiest scenario, higher temperatures were also investigated. The reason behind is the possibility of taking profit of any low/middle-grade waste heat in the industrial processes and use the slag to increase its temperature and up-grade the waste heat stream (improve heat quality/entropy).

First set of experiments had as main objective the evaluation of the maximum energy that can be recovered as a function of the charging temperature of the slag. The results discussed in this section correspond to the experiments 1 to 3 numbered in Table 1. In these experiments, all the conditions were the same with the only difference of the temperature used in the slag charging. The slag charging temperatures tested were 500, 400 and 200°C. In all cases, air at room temperature was used in the discharging process. Temperatures recorded inside the tank during the discharging process are included in Figure 5. Furthermore, the inlet and outlet temperatures are also plotted for discussion. Second set of experiments had as main objective the evaluation of the effect of the temperature level at which the heat recovery process is carried out. For this purpose, the ΔT between the slag initial temperature and the discharging temperature is kept in 200°C. In this regard, the investigated temperature ranges are room-200°C, 200-400°C and 300-500°C. In these three experiments, the rest of experimental conditions were the same. Results of experiments 4 and 5 (see Table 1) are presented in Fig. 6. Curves corresponding to the experiment between room-200°C have already presented in Fig. 5.

It can be noted that temperatures included for each thermocouple position in these graphs correspond to the average value between radial positions A to D (see **Error! Reference source not found.**). E temperatures have not been considered as, this position is very close to the tank's wall and the measured temperatures are highly affected by wall effects (thermal losses, higher velocities…). It can be noted that, while temperatures registered from A to D vary no more that 1-2°C between them, which represent the behaviour of the bulk, the temperatures of the E position are always around 10°C lower than the bulk. In order to compare between different experimental conditions, a criterion for assuming the cooling process as completed should be stablished. This criterion will be imposed by the final application of the captured heat. For the comparison analysis carried out in this work, a minimum temperature at the tank's outlet has been fixed, i.e. 50°C. In this regard, the slag is considered as completely cooled down, once the air temperature in the tank's outlet drops below 50°C.

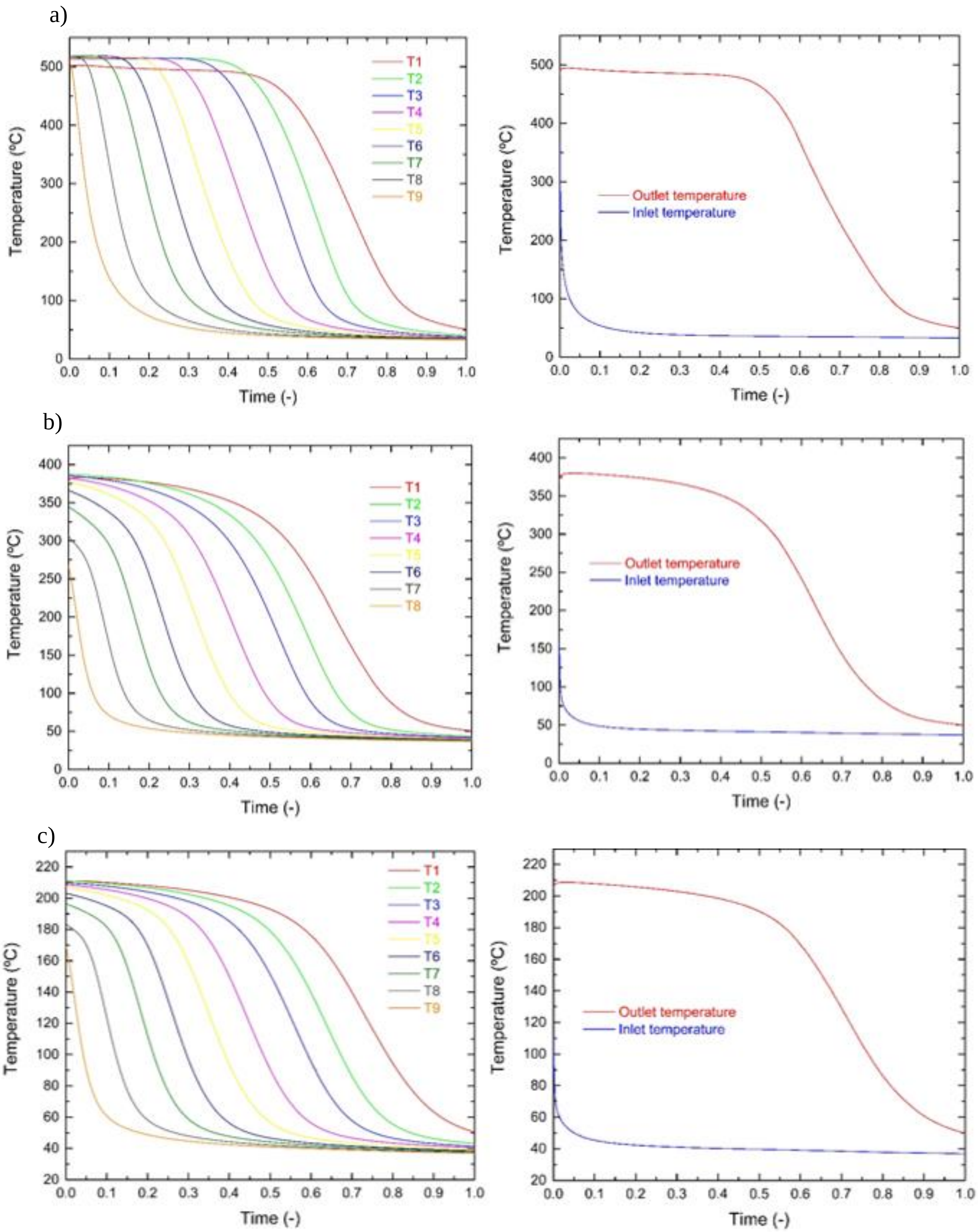

Fig. 5. Discharging experiments at room temperature: a) TES charged at 500°C, b) TES charged at 400°C and c) TES charged at 200°C

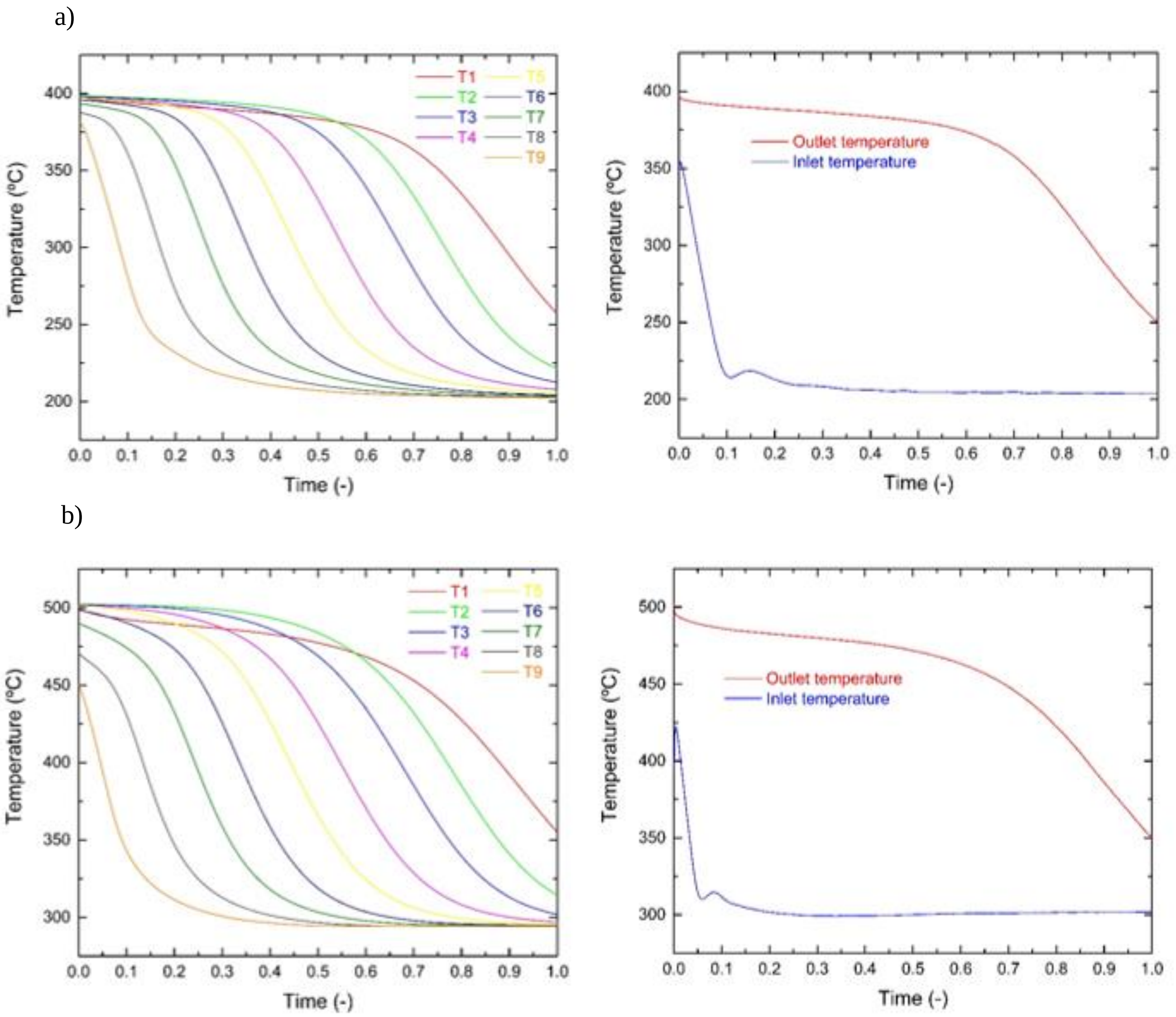

Fig. 6. Discharging experiments with 200°C of ΔT: a) TES charged at 400°C, b) TES charged at 400°C and c) TES charged at 500°C

In order to compare between the five experiments, the recovered energies and the efficiencies of the complete process are included in Table 2. Looking at the recovered energies, as expected, the higher is the initial temperature of the slag, the higher is the recovered energy as well. However, looking at the recovery efficiency, higher values are observed when lower is the initial temperature of the slag. This result is justified by two phenomena. On the one hand, the slag low thermal conductivity presents a barrier to the heat recovery process. Taking this into account, when larger is the ΔT between the slag and the cooling air, more heat exchange area is required for an effective heat recovery process. And, on the other hand, the lower efficiency is justified by the fact that, when higher is the slag temperature, higher are also the thermal losses, which in this case accounted for around 0.85 kW. In this regard, more energy is released from the slag to the atmosphere and, therefore, lost. In the case of the experiments with discharging temperatures above room ones, it is found that, even if the expected recovered energies in the two cases would be expected to be similar due to the same ΔT, relatively higher energies are recovered when lower is the temperature level. This result is clearly aligned with the recovery efficiency. When lower is the initial temperature of the slag, higher is the efficiency. This result clearly shows again the impact of the thermal losses in the heat recovery process.

Table 2: Recovered energy and process efficiency discharging at room temperature

Experiment number	Charging temperature (°C)	Discharging temperature (°C)	Initial TES energy (kWh)	Recovered energy (kWh)	Recovery efficiency (%)
1	500	Room	343.4	262.2	76.4
2	400	Room	202.0	164.9	81.0
3	200	Room	122.1	117.6	96.3
4	400	200	147.4	102.0	69.2
5	500	300	152.6	96.3	63.1

5. System upscaling and cost analysis

In order to assess the economic viability of a slag-based TES system it is recommendable to set a frame and focus the analysis to a given application, which may be used as a reference value. For that reason, the analysis will be carried out under the scope of the waste heat recovery plant addressed in the LIFE HI4S project for the steel making industry. This concept is based on recovering the intermittent waste heat content in the electric arc furnace (EAF) off-gas stream, store it in a TES system, and subsequently, use the heat to preheat the scrap that would be used in the following casting. Therefore, the stored energy will save the corresponding electric energy that otherwise would be needed in the EAF to reach the same energy level in the scrap.

Considering a steelwork operating 1 EAF of 100 tonnes, with an average waste heat content in the off-gas stream of 200 kWh/tonne of steel at 750°C [8], the total waste heat released per casting may account for 20 MWh. Setting at 500°C the maximum TES operation temperature to avoid the use of expensive materials, the resulting recoverable energy would reach up to 14 MWh per casting. In order to transfer all this energy to a slag-based TES and considering a 40% of void fraction, a TES volume of 100 m^3 with 140 tonnes of slag would be required. Since the slag is a by-product and large amounts are still landfilled, its cost can be assumed by the steel producer. Therefore, the thermal storage material cost is considered negligible for TES CAPEX analysis and the investment cost will be essentially constituted by the cost of the vessel, piping, installation and its thermal insulation. Considering the volatility of the raw material cost, we base our calculation on an estimation from [9], where an average cost of 8.62 €/kWh is set for a thermocline TES, comprising the raw vessel material, piping, manufacturing, installation, and insulation. Consequently, considering an inflation from 2017 of around 6%, the resulting investment cost accounts for 127 k€.

Since most of the steelwork industry works in a continuous operation mode during a whole year, with 1 hour per casting, a yearly production around 750,000 tonnes of steel may be expected, releasing 107 GWh/year of waste heat at around 500°C. Considering the scenario where the energy is reused within a temperature range of 500-300°C, with a 63.1% efficiency loss during discharging observed during our experiments, 3 GWh may still be reused. According to data provided by Eurostat, the average electricity price value in Europe at present is 0.2104 €/kWh [10] and therefore, the recovered waste heat may save up to 630 k€ per year, which is much higher compared to the 127 k€ investment cost of the TES system.

4. Conclusion

This work presents the results obtained in an experimental campaign comprising the charging and discharging of a slag-based thermal energy storage of 400 kWht, using air as heat transfer fluid. The results proved the viability of using steel slag as a thermal energy storage material. Nevertheless, the prototype showed efficiencies ranging from 63.1 to 96.3 %, highly dependent on the temperature level. Thermal losses due to radiation were identified as the main reason of efficiency loss and therefore, it should be tackled in the scaling up of the system. Furthermore, the cost analysis of such a thermal energy storage system was set at 6.35 €/kWh, which for a specific industrial waste heat recovery application and even considering the worst performance scenario, make the solution highly competitive.

Acknowledgements

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