Novel heat recovery system for ceramic furnaces using high-temperature phase change materials and integration based on multicriteria analysis development

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Abstract

Waste heat recovery is one of the solutions included in the roadmap for reducing both energy consumption and the carbon footprint. Its high replication capacity in steel, ceramics, pulp and paper, and other energy-intensive industries favours the efficiency of the process and, consequently, achieves reductions in consumption, pollution and the equipment size and cost. As a result, the large-scale deployment of those innovative technologies is determinant for achieving energy efficiency and climate changes objectives in an effective and efficient manner. In this vein, VULKANO and RETROFEED projects implements and validates an advanced retrofitting solution to improve the overall efficiency and reduce emission in intensive sectors. On this route, a novel high-temperature Phase Change Materials (PCMs)-based thermal energy storage system (TES) for industrial furnaces is evaluated to increase the energy and environmental efficiency by recovering waste heat from the combustion gases. Design details such as preliminary sizing, costs and conceptual design configuration is presented as an example of integration at industrial scale, adapted to the plant operational requirements, by searching the best conceptual design and a proper selection of core materials. A multicriteria analysis is developed and applied to select the most profitable system configuration. The methodology is based on technical indicators, that is, life cycle assessment, life cycle cost, and techno-economic analysis, to assess both the status quo of existing gas furnaces and their modification after incorporating the PCM-TES. The potential for improving efficiency, reducing environmental impact and cost savings is determined by implementing the waste heat recovery system. Consequently, this methodology considers and integrates the analysis of horizontal and vertical value chain that can be used as a prefeasibility analysis based on a decision support tool for defining reproducibility and replicability.

Keywords

High temperature thermal energy storage, waste heat recovery, phase change materials, energy-intensive industry, multicriteria analysis, system integration.

1. Introduction

Energy-intensive industries (EII) account for 80% of the total industrial energy consumption becoming in one of the focus for successful energy and environmental efficiency strategies. The energy-intensive industries have different waste heat sources variables in time, flow and temperature. Although significant efforts have been invested in the development of new waste heat recovery (WHR) technologies during the last years, their implementation in industrial environments, in parallel with decision support tools, are still very limited. Among the WHR technologies, there is a novel tendency to introduce thermal energy storage systems (TES) based on latent heat to improve the waste heat recovering at medium and high temperatures. Latent heat storage based on phase change materials (PCMs) became a potential technique for storing and recovering waste heat. Compared to sensible heat techniques, latent heat is characterised by its higher energy storage density, storing thermal energy at a constant temperature, increasing the system flexibility and exhibiting acceptable long-term reliability [1].

Although there is a lack of studies of PCM-TES performed at high temperature, some authors provided insights in this field at different working conditions. For instance, at low temperatures, Tay et al. [2] experimentally tested a TES system based on cylindrical tube-in-tank design filled with PCM obtaining a characteristic design curve as a function of the measured average NTU. Other important aspect is the system configuration and design to improve the heat transfer in the heat exchanger (HX) especially between the PCM and the surrounding fluids.

Based on the previous research, the proposed PCM solution aims at recovering the thermal energy at high temperature from an off-gas or surplus from a fossil fuel fed furnaces installed in an industrial plant. Therefore, a key point for system designing is a proper selection of core materials working as PCM. In this sense, this paper proposes a suitable PCM working at high temperatures as presentation of a study case. Additionally, selecting the most profitable concept design and materials requires a broad perspective considering not only technical aspects, but also economic and environmental issues. Therefore, this study discusses under a multicriteria perspective the methodology results based on a techno-economic analysis and environmental assessment to determine the potential for improving efficiency, reducing environmental impact and cost savings.

2. Methodology

2.1 PCM feasibility and replication tool

This study shows the use of a computational tool used to define a customized design sizing, the selection of a proper PCM and also simulate the resulting operation performance and impacts of the system. The tool is implemented in MATLAB software and the core algorithms of this feasibility and replication tool are based on correlations obtained from simulating and modelling numerous study cases considering PCM-system integration. These studies were performed under a variety of working operation conditions at high temperatures and using different PCM materials for storage the wasted heat in several EII [3]. The obtained results are analysed and used to feed the tool core and find representative correlations.

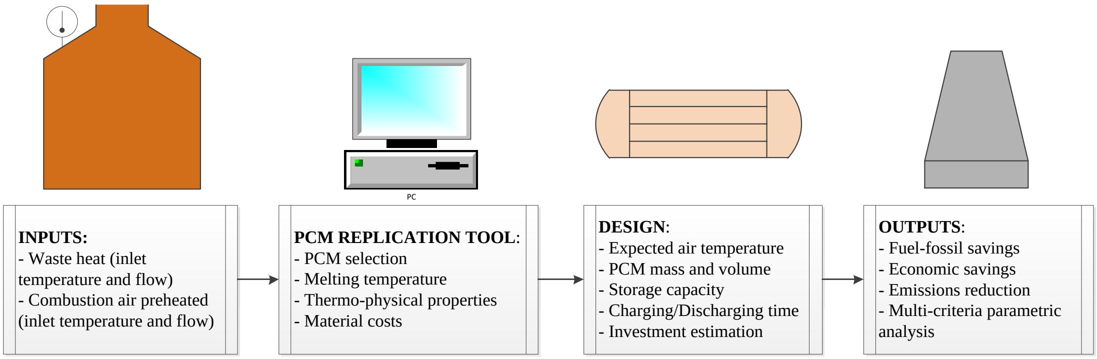

Figure 1. Diagram of the inputs and outputs for the prefeasibility and replication tool.

The tool basis relies on a mathematic-based information analysis technique, which consists of analysing the relationship between the most relevant parameters on PCM-system modelling, e.g. temperature and flow of stream, PCM melting temperature, thermal conductivity and storage capacity. The relationships between the different variables may be linear, polynomial, logarithmic, potential, etc. and the selection of the suitable correlations consists of ensuring high correlation coefficient (R^2) values and minimising the deviation of the relationship calculated compared with the detailed simulation results.

The replication tool is capable of defining a preliminary design and expected resulting impacts from the system in function of the inlet temperature and flow of the wasted flue gases, the available volume in the plant to install a PCM-TES system and the desired use of the recovered heat. On the one hand, the outputs from the computational tool involve technical and design parameters (namely PCM mass, volume of system, temperatures of flue gases outlet, real temperature of the air stream outlet, charging and discharging times, etc.). On the other hand, impacts resulting from the operation with PCM-TES integration include economic and environmental savings.

2.2 Preliminary sizing and PCM selection for the storage system

The results are mainly based on the correlations along with a suitable PCM selection. The procedure explained by Royo et al. [3] is followed to determine the required storage capacity of the PCM-TES system. The discharging releases the accumulated heat to the air stream increasing its temperature, while the liquid PCM becomes solid again. Then, the heat demand of the air preheating is equivalent to the thermal energy released by the PCM during the discharging (Q_{dis}) and it is quantified by Eq.(1), considering the combustion air flow (m_{air}) preheated, the specific heat ($c_{p.air}$) and the temperature increase achieved due to the PCM-TES integration (ΔT_{air}). This increase can be ideally calculated as the difference between the PCM melting temperature and the inlet air temperature.

$$Q_{dis} = m_{air} \cdot c_{p.air} \cdot \Delta T_{air} \tag{1}$$

Similarly, Eq.(2) determines the thermal storage capacity available during charging (Q_{char}), which is taken from the stream of wasted flue gases after the PCM has accumulated the recovered heat. Q_{char} is defined in function of the flue gas mass flow (m_{fg}); the specific heat ($c_{p,fg}$) and the temperature increase in the flue gases stream (ΔT_{fg}) This increase can be ideally calculated as the difference between the flue gas stream temperature at the system outlet and the melting temperature of the PCM.

$$Q_{char} = m_{fg} \cdot c_{p,fg} \cdot \Delta T_{fg} \tag{2}$$

The ideal charging and discharging times can be calculated using the previous equations and considering the storage capacity of the system (Q_{LHS}). However, in order to adapt it to the reality, the tool uses correlations to include the effect of system efficiency and the heat transfer area of the studied PCM-TES configuration. A sensitivity analysis was conducted to figure out the most relevant parameters affecting the correlations, which are the thermal conductivity, volume and storage capacity of the PCM.

The PCM-TES sizing is determined in function on the assumption that the heat demand is covered only by the fusion latent heat (Q_{LHS}), and its latent heat of fusion of the PCM (H_{fusion}), which defines the required PCM mass (m_{PCM}) with Eq.(3). In this vein, the volume PCM for each specific application can be calculated according to its density:

$$m_{PCM} = \frac{Q_{LHS}}{H_{fusion}} \tag{3}$$

The investment is calculated considering both the costs of the storage core material (that is the PCM itself) and the containing infrastructure as a fixed cost in addition to a ratio in function of the required PCM volume. In the economic assessment, the fossil-fuel savings due to the waste heat recovery are considered as savings, and the PCM-TES system considers a lifespan of 20 years.

Finally, for the environmental assessment the global warming indicator has been selected as one of the more relevant for this analysis due to the raising awareness of climate change. To do so, the ReCiPe method evaluated with SIMAPRO software is used to calculate the equivalent CO_2 emissions. Moreover, if during the evaluation any other environmental indicator is found to be relevant, it would be highlighted.

3. Results and discussion

3.1 System description and PCM-TES conceptual design

A PCM-TES is incorporated in an industrial plant, as shown in Figure 3, close to the melting furnace in order to recover heat from the exhaust gases after combustion. In this case, the main objective of the PCM configuration is preheating the combustion air to improve the efficiency. gathers the main parameters for the inputs and the expected desired outputs. The preliminary sizing and the conceptual design are fed by the parameters illustrated in Figure 3.

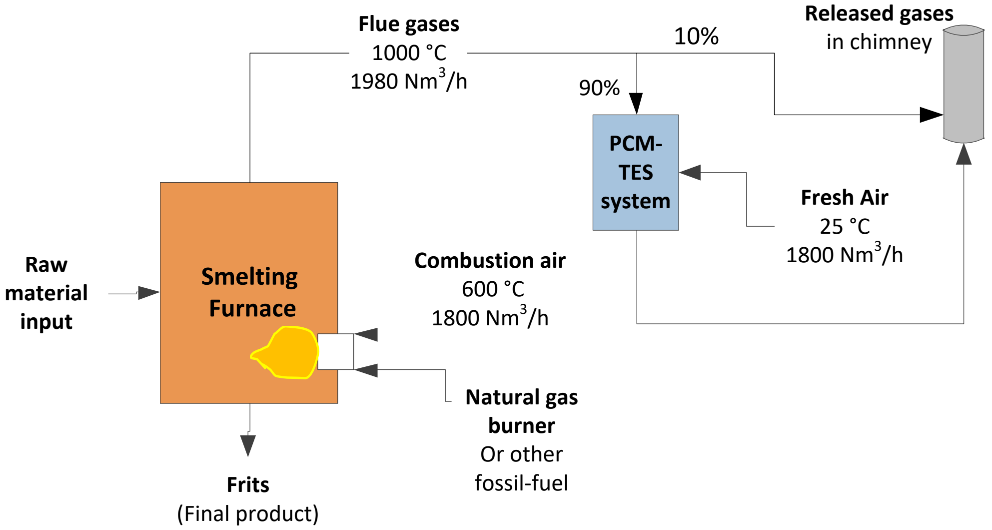

Figure 2. Diagram of the heating system with the PCM-TES integration.

Thereby, a PCM with a melting temperature around 600 °C or more will be selected as core material of the PCM recovery system. As conceptual idea and preliminary calculation purposes, it was assumed the PCM system could release a constant combustion air temperature. Moreover, negligible transference losses in PCM solution were considered.

The present system is composed of several double concentric tubes embedded in a shell. The hot waste flue gases flow vertically inside the inner part of the tube. This tube is surrounded by a ring-shape layer of PCM, which is in contact with the flue gases and store the heat transferred by conduction. Then, the air stream to be preheated flows through the external shell, and the PCM releases the heat while decreasing its temperature by means of convection. Besides, baffle along the shell are introduced in order to enlarge the heat transfer time and achieve a greater temperature increase. This configuration allows the disassembly for maintenance labours or PCM replacement, if needed. More detailed characteristics of the selected configuration system are described and illustrated in Royo et al. [4].

3.2 PCM parametric analysis

In the following sub-section, it is presented the PCM selected for the application considering (i) release and absorb large amounts of energy when they solidify and melt; (ii) have a fixed and well-defined phase change temperature (solidification/melting point); (iii) avoid excessive super cooling and remain stable over many freeze/melt cycles; (iv) be non-hazardous and non-corrosive to its encapsulating material and (v) be profitable for a given application. It an inorganic salt, composed of a mixture of carbonates, more specifically (Na_2CO_3 + K_2CO_3 + Li_2CO_3), whose properties are determined in Table 1.

Table 1. Main properties of the PCM selected for the parametric analysis [5].

PCM type	Melting point (°C)	Latent heat (kJ/kg)	Density (kg/m^3)	Thermal conductivity (W/m K)	Cost (€/kg)
Hydrated salt HS2	687	300	2450	0.557	0.25

The tool determines the most relevant sizing and design parameters (Table 2) based on a shell and tube configuration with the PCM encapsulated in double concentric tubes according to the methodology previously presented; considering the thermo-physical and economic properties of the selected PCM (Table 1) and an energy demand of 393 kWh/h, according to the system requirements (Figure 3).

Table 2. Main design, performance and costs parameters from the parametric analysis performed by the prefeasibility and replication tool.

Design Parameter	PCM-inorganic salt
Mass of PCM (kg)	4716
Volume of PCM (m^3)	1.93
Cost of the PCM (€)	1179
Cycles (cycles/day)	2.85
Preheated combustion air temperature (ºC)	625

Salt hydrates are inorganic PCMs that have been extensively studied in heat storage applications because of their positive characteristics and are known for their high storage density (175-225 kJ/kg) and abundant availability. Usually, the cost of the hydrated salt is cost-effective in the market [6]; however, the low thermal conductivity represents its major drawback. This would result in long charging and discharging periods (hours); while other options, such as metals, would involve much faster cycles (minutes). Other particularity is that the volume of these salts changes greatly when changing phase during subcooling and incongruent segregation [7]. Therefore, apart from the PCM selection, the design phase of the TES system is crucial to ensure a proper heat transference between the HTF and the PCM.

3.3 Key indicators evaluation

Based on the previous results, it is calculated relevant indicators from the technical (energy and fuel savings), economic (cost investments and savings) and environmental (evaluation of PCM in function of its nature and the natural gas saved) perspectives. For the calculation, it is assumed the same energy demand, 261 working days per year, 20 years of system lifespan, LHV (Lower Heating Value) of natural gas of 38.63 MJ/Nm^3 and a cost of 0.42 €/Nm^3 of natural gas.

Table 3. Key indicator evaluation results in function of criteria weighting.

Key indicator results	PCM-inorganic salt
Energy saved (MWh/year)	437
Net economic saving (k€/year)	9.2
€ NG saved / € Investment	2.0
Total environmental impact of PCM (t CO_2 eq)	11
Environmental impact NG saved (t CO_2 eq / year)	-106

As a result of the evaluation, the performance of the inorganic salt resulted in nearly 440 MWh saved per year. This salt presents a not very high ratio between discharging and charging periods (0.22) meaning that it needs much longer times for charging than discharging. This fact is mainly due to the low thermal conductivity (0.557-1 W/m·K). It would be recommendable to consider techniques of conductivity enhancement, such as the integration of metallic mesh or foams with high conductivity, integration of fins to increase the heat transfer area or even the introduction of nano-particles of graphite or other highly conductive materials. These methods would allow an increase in the energy saved per cycle.

In economic terms, the savings are calculated based on the reduction of the fossil-fuel consumption due to the integration of the PCM system. Hence, this would result in an annual saving of 9200 € for the industrial plant, considering that a total of 2.85 cycles can be conducted daily in a continuous mode of operation. Another important value to consider when comparing the system behaviour is the ratio between the fuel consumption savings and the economic investment. For the selected PCM, 2€ of NG are saved per each unit invested for the PCM-TES system.

Regarding the environmental perspective, the hydrated salt production itself presents a carbon footprint 11 t CO_2 eq. These values were calculated considering the impact of manufacturing the PCM quantity required for the studied PCM-TES configuration in function of the volumetric capacity. Ferreira et al. [8] conducted an analysis of the environmental behaviour of four PCM-TES systems varying the type of inorganic salt incorporated obtaining very promising results. Among them, a mixture similar to the one studied in this work was also analysed, whose environmental behaviour resulted in 47 kg CO_2 eq /MWh of energy stored; while in the present study case this ratio is 25 kg CO_2 eq /MWh. The deviations come from the different configuration for the PCM-TES, the PCM composition varies between the study cases, and the SIMAPRO software database are from different versions too. All in all, it is considered an acceptable result for comparison. Moreover, an aggregated GHG reduction of around 2120 t CO_2 eq, is obtained during the PCM-TES lifespan (Table 4). The GHG emissions saved every year due to impact avoided is calculated from the natural gas extracted, transported and burnt.

4. Conclusions

Implementing PCM-TES is foreseen as one innovative retrofitting option for reducing energy consumption and improving the carbon footprint in EII. In this work, a multicriteria assessment was conducted based on a suitable PCM selection and the use of an intuitive and simplified computational tool. The outputs from the tool allows analysing from different perspectives, including technical, economic and environmental impacts and results. This serves as a first approach and a prefeasibility study that provides an idea of the expected performance of integrating a PCM-TES at an industrial plant. Concretely, an exhaustive evaluation was presented regarding the main benefits and limitations related to their optimal applicability at industrial scale.

Results illustrated in this case the use of an inorganic hydrated salt. This alternative presented the highest net economic savings (near 92000 €) and the greatest energy savings (440 MWh/year). This configuration was identified to provide the good environmental performance with a GHG reduction of up to 2120 t CO_2 eq. during its lifespan due to the NG saving. The comparison with previous environmental studies, resulted that the selection of carbonate salts would be more convenient than other inorganic salts compose of nitrates (KNO_3) and hydroxides (LiOH, KOH).

Finally, a parametric analysis will be performed in future research by means of a comparison of alternative types and nature of PCM and different working conditions (temperature and mass flow of gases to be recovered) as inputs of the tool. Furthermore, in order to ensure design robustness and wider replicability, future work should analyse PCM-TES integrated system operation parameters, under different working conditions (typical, process temperatures, flows, time mismatch, volumes). This would allow to enhance the tool response getting more accurate and reliable results for more industries and production conditions; thus, increasing its replicability.

Nomenclature

c_p	Specific heat
EII	Energy-intensive industries
GHG	GreenHouse Gas
H_{fusion}	Latent heat of fusion of the PCM
HTF	Heat Transfer Fluid
HX	Heat eXchanger
LHS	Latent Heat Storage
LHV	Lower Heating Value
m	Mass or mass flow
NG	Natural Gas
PCM	Phase Change Material
Q	Heat demand
TES	Thermal Energy Storage
$\Delta T_{.air}$	Temperature increase in the combustion air
ΔT_{fg}	Temperature decrease in the flue gases stream

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