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PCM-based energy recovery from electric arc furnaces

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HIGHLIGHTS

- A device based on phase change materials to smooth off-gas temperatures is proposed.
- The smoothed temperature profile allows an effective downstream energy recovery.
- Containers configuration and layout are analyzed by thermo-fluid dynamic simulations.
- The energy recovery system is sized with a new boiler arrangement to reduce off-gas dust content.

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ABSTRACT

The problem of energy recovery from the electric arc furnace process of steel industry is addressed. During a tap to tap cycle, a significant part of the energy required for steel production is dissipated by the off-gas. The high variability of temperatures and flows, and the high concentration of dust, which characterize the production process, make the adoption of current energy recovery solutions quite difficult, both from the technological and the economical perspective.

A new system is proposed exploiting the characteristics of phase change materials (PCM), in particular aluminum, to reduce the variability of off-gas temperatures and thermal powers, in order to allow an efficient energy recovery. The smoothing device is analyzed by thermo-fluid dynamic simulations in order to optimize its performance. A new boiler configuration equipped with cyclones is proposed to overcome also the problem of high dust content of the off-gas.

The high recovery efficiencies, the low investment and operation costs and non-invasive plant modifications induced by the smoothing system, make the proposed PCM-based recovery system a feasible solution to reduce energy supply costs and emissions in the steel industry.

1. Introduction

Steel industry is considered an energy-intensive sector, representing a major consumer of electricity and one of the largest producers of greenhouse gas (GHG) emissions. World steel production increased from 28 million tons in 1950 to nearly 1.51 billion tons in 2012 [1]. Both current and future energy-related scenarios (growth of energy demand, production costs, and pollution) claim for more rational use of energy in order to foster sustainable development. Therefore, efforts should be focused on improving energy efficiency in steel production and energy recovery should become a major issue to be addressed.

The total energy required by an electric arc furnace (EAF) process typically ranges from 510 kW h/t to 880 kW h/t [2]; the minimum energy required to melt the scrap and to superheat the melt and basic slag to 1600 °C is approximately 444 kW h/t [3]. Energy consists for 40–65% of electrical energy, and for 22–60% of thermal and chemical energy generated from oxidation reactions during refining. Only the 50–70% of the output energy is represented by steel and slag enthalpies, while the remaining part is dissipated by the water cooling systems of the furnace (10–20%) and by the off-gas (15–35%) [2]. This means that potentially a portion of about 25–55% of the input energy could be exploited by energy recovery.

Different technologies have been developed for the exploitation of the large enthalpy content of off-gas. The most common are those involving pre-heating of the scrap before its charging into the furnace: Consteel® [4] and Consteel® Evolution™ process [5], Finger and Double Shaft Furnace system [6], Twin-Shell technologies [7], EPC® system [8], and the Ecoarc™ furnace [9]. Despite of considerable advantages, such as the reduction of the tap-to-tap (TTT) cycle time, the decrease of the electricity demand, and of

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the CO_2 emissions [10,11], these techniques present problems that have hindered their effective development and use. Most difficulties concern plant complexity, as well as surface oxidation of the charge, its partial melting, high emission factors for dioxins [12].

Off-gas recovered energy could be exploited also for production of electric energy by a Rankine cycle, for creating vacuum in VD/VOD plants, for process heating (e.g. steel pickling bath, sea water desalination, pulp, and paper industry) and for district heating [13]. However, all these potentials uses require a constant supply that cannot be assured by the EAF process. Many attempts have been made to reduce this variability, most of which based on steam storage [14]. Other systems, for example the Simetal EAF Quantum™ technology [15], employ molten salts to support superheating of the steam feeding the turbine or even as heat transfer fluid [16]. Even SMS Siemag AG has introduced a technique that involves a downstream steam accumulation system to reduce the variability of steam supply to the turbine [17]. However, these systems are rather expensive and enhance plant complexity.

As highlighted in [18], the most modern installations in the EU steel industry are close to the limits of what current technologies can do, and the steel industry will struggle to achieve further energy efficiency improvement without the introduction of breakthrough technologies.

We propose a system based on phase change materials (PCM), which, by accumulating and releasing large amounts of energy, acts as a "thermal flywheel", thus allowing to smooth off-gas temperatures. Temperature smoothing is achieved by directly operating on off-gas unlike the other current technologies and it is separated from the downstream energy conversion system, based on a traditional Rankine cycle but with an innovative boiler structure. This allows a non-invasive intervention on the system with minimum plant modifications. The simple structure, the low cost of operation, and the high recovery efficiency can make this just patented [19] recovery system a feasible solution to increase energy efficiency in steel industry.

The paper is organized as following. In Section 2 the smoothing system concept based on PCM properties is proposed; in Section 3 the preliminary analysis of the system with thermodynamic simulations is reported, while in Section 4 the final configuration of the PCM containers and their layout is described with related performance. In Section 5 the downstream recovery system is introduced and properly sized, while the economic analysis of the overall system is reported in Section 6. Finally, conclusions are summarized in Section 7.

2. The PCM-based smoothing system concept

To design the energy recovery system, we referred to a typical EAF steel plant with 120 tons per TTT cycle capacity and 68 min TTT cycle time, whose off-gas cleaning section is shown in Fig. 1. After passing the settling chamber and the cooler, off-gas of the primary line joins the secondary line one, which was captured during the furnace roof opening phase, and proceeds to the cyclonic separator and the filter.

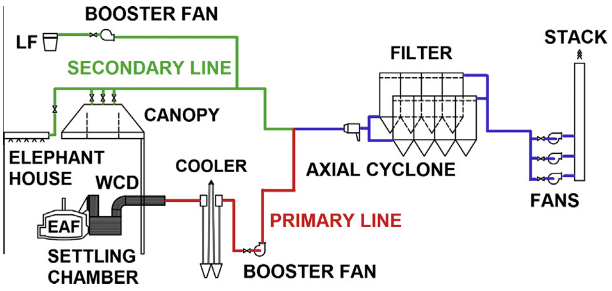

Fig. 1. Off-gas cleaning section of the reference EAF steel plant.

Table 1
Off-gas properties.

Average temperature (°C)	600
Rate flow (Nm^3/h)	166,700
Normalized density (kg/Nm^3)	1.3
Specific heat capacity ($J/(Nm^3 K)$)	1330
Thermal conductivity (W/(mK))	0.051

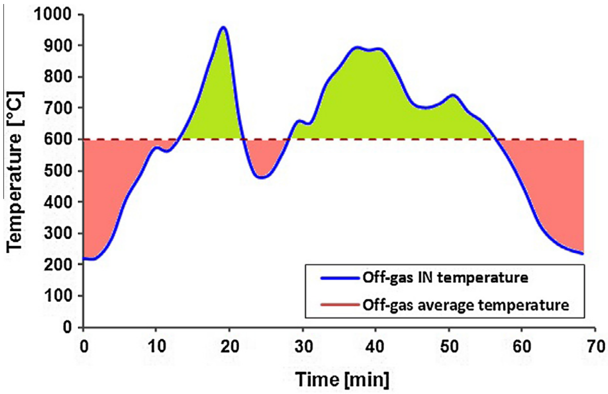

Fig. 2. Off-gas temperature profile at the chamber inlet in the reference TTT cycle; in green energy potentially accumulated by the PCM, in red energy released by the PCM. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

The analysis of the new recovery system is based on the experimental data provided by an Italian firm and measured at the inlet section of the settling chamber during several castings (see Table 1 for average values of off-gas properties and Fig. 2 for temperature pattern). Similar variability in off-gas flow and temperature was obtained in [20].

The characteristics phases of a melting cycle can be clearly recognized in the temperature profile in Fig. 2. The two temperature increases (from 220 °C to 950 °C and from 485 °C to 885 °C) correspond to the melting of the first and second bucket, respectively. The two decreases (from 950 °C to 485 °C and from 885 °C to 230 °C) correspond to the charging and to the tapping phase, respectively. The small drops around 570 °C and 655 °C are related to burners opening.

To achieve an efficient energy recovery from EAF off-gas, its temperature variability range should be properly reduced. We propose the adoption of a PCM-based device located in the settling chamber, which captures thermal energy from off-gas and return it to off-gas later, acting as a heat accumulator. During the phases at high temperature, off-gas raises the temperature of the PCM above its melting temperature, causing the transition from the solid state to the liquid one with accumulation of the latent heat of fusion. During the phases at low temperature, off-gas causes the PCM transition from liquid to solid state with release of the latent heat of solidification (see [21] for a review on PCM properties and issues for latent heat storage).

Off-gas energy is approximately proportional to the area under the temperature curve. In particular, the portion above the average off-gas temperature, supposed to be near the PCM melting value (green area in Fig. 2), can be considered as representative of the energy that can be subtracted from off-gas and accumulated by the PCM. The portion below the average temperature (red area in Fig. 2), instead, describes the latent heat of solidification that can be released to off-gas by the PCM, whenever its temperature profile decreases below its melting point.