Energy Conversion and Management 104 (2015) 78–89

Contents lists available at ScienceDirect

Energy Conversion and Management

journal homepage: www.elsevier.com/locate/enconman

Enhancing energy recovery in the steel industry: Matching continuous charge with off-gas variability smoothing

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ARTICLE INFO

Article history:
Available online 19 May 2015

Keywords:
Energy recovery
Steel industry
Electric arc furnace
Off-gas
Phase change materials
Heat transfer fluid
Variability smoothing

ABSTRACT

In order to allow an efficient energy recovery from off-gas in the steel industry, the high variability of heat flow should be managed. A temperature smoothing device based on phase change materials at high temperatures is inserted into the off-gas line of a continuous charge electric arc furnace process with scrap preheating. To address overheating issues, a heat transfer fluid flowing through containers is introduced and selected by developing an analytical model. The performance of the smoothing system is analyzed by thermo-fluid dynamic simulations. The reduced maximum temperature of off-gas allows to reduce the size and investment cost of the downstream energy recovery system, while the increased minimum temperature enhances the steam turbine load factor, thus increasing its utilization. Benefits on environmental issues due to dioxins generation are also gained.

1. Introduction

The current economic crisis in the European Union has caused the steel sector to face a reduction of steel demand of about 27% in comparison to pre-crisis level. As a consequence, several production plants have been forced to close or reduce output, with up to 40,000 jobs lost in recent year [1]. Thus, the European steel industry has to face the simultaneous effects of low demand and overcapacity in a globalized steel market, whilst confronting high energy prices and the need to comply with the green economy. In such an energy-intensive sector, energy efficiency becomes a key objective, which is able to gain both cost savings and greenhouse gas (GHG) emission reduction, thus pursuing sustainability in its multiple dimensions [2].

It has been estimated that 25–55% of the energy used in electric arc furnace (EAF) steelmaking processes is lost in the form of hot exhaust gases, cooling water and heat losses from equipment and products [3]. As highlighted in [4], recovery of energy from EAF steelmaking processes represents the greatest single opportunity for reducing energy use. Nevertheless, most modern installations in the EU steel industry are close to the limits of what current technologies can do, and the steel industry can hardly achieve further energy efficiency improvement without the introduction of breakthrough technologies. The main issues to be overcome are the high variability of off-gas temperature and flow rate, and the high concentration of dust, which affects the efficiency of the heat exchangers and the downstream power production system components (turbine, evaporative tower). From the economical point of view, an inefficient recovery system leads to high payback periods, thus reducing its actual implementation.

The aim of this study is to enhance energy recovery from the EAF process due to the introduction of a smoothing system based on phase change materials (PCMs) acting on the off-gas temperature profile. Energy recovery performance is increased by introducing a heat transfer fluid through PCM containers, which enables the adoption of smaller pipe diameters while overcoming overheating issues.

After revising literature about current off-gas energy recovery technologies in Section 2, in Section 3 the process description and the adopted methodology in order to develop the PCM based energy recovery system are exposed. In Section 4 the preliminary analysis of the system is performed, followed by system improvement in Section 5. The final system configuration and energy recovery results are provided in Section 6, while conclusions are summarised in Section 7.

2. Energy recovery from EAF off-gas: state of the art

Current available technologies for energy recovery from off gas of the EAF steelmaking process can be classified depending on the final use of recovered heat (see Table 1).

In direct recovery, off-gas thermal energy is recuperated without the introduction of a heat transfer fluid (HTF) and directly used

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http://dx.doi.org/10.1016/j.enconman.2015.05.012
0196-8904/

Nomenclature

Acronyms

EAF	electric arc furnace
EU	European Union
GHG	greenhouse gas
HTF	heat transfer fluid
LHS	latent heat storage
PCM	phase change material
TES	thermal energy storage
TTT	Tap to Tap
UDF	User Defined Function

Latin letters

c	specific heat (J/kg K)
D	outer diameter (m)
d	inner diameter (m)
f	friction factor
h	chamber height (m)
L	heat exchange length (m)
$\dot{m}$	mass flow rate (kg/s)
Nu	Nusselt number
p	pressure (MPa)
Pr	Prandtl number
q	heat transfer rate (W)
q''	heat flux (W/m^2)
Re	Reynolds number
S	pitch (m)
T	temperature (°C)
t	thickness (m)
U	overall heat transfer coefficient (W/m^2 K)
v	average velocity (m/s)
y^+	dimensionless wall distances

Greek letters

α	convection heat transfer coefficient (W/m^2 K)
λ	thermal conductivity (W/m K)
ρ	density (kg/m^3)
μ	viscosity (kg/m s)
Δ	properties difference

Subscript

e	external tube
F	flow
H	heat transfer fluid
i	internal tube
in	tube inlet
m	mean
ml	mean log
out	tube outlet
w	wall
T	transversal
L	longitudinal
P	phase change material

to preheat the scrap before its charging into the furnace. As shown in Table 1, related technologies can be further classified into two groups based on the type of scrap charging, which can be continuous or discontinuous. Direct recovery in discontinuous charging is mainly carried out by means of two technologies: shaft furnace and twin-shell. For what concerns shaft furnace technologies, two main arrangements can be considered: single shaft, in which the shaft (water cooled and refractory lined) is situated on top of the EAF, and double shaft, which consists of two EAF furnaces, each with a shaft and one common electrode mast and set of electrodes to serve both furnaces [5]. Similar to the double shaft technology, twin-shell technology includes two EAF vessels with a common arc and power supply system [6].

The main technologies for direct heat recovery in continuous scrap charging are: Consteel, Ecoarc and EPC. In Consteel technology, the scrap is loaded onto a charge conveyor and pre-heated in a tunnel by process off-gas while it is continuously fed into the EAF, where it is melted by immersion in liquid steel [7]. Its evolution consists of wider conveyors to increase the exchange surface, a different tunnel profile to improve the convective heat exchange, and a new tunnel section equipped with burners, to boost chemical energy input [8]. In Ecoarc technology, scrap is continuously fed into the preheating shaft and is in constant contact with the molten steel in the melting chamber; during the melting phase the furnace including the shaft is tilted backwards [9]. The EPC technology consists of two main components, the preheating chamber with its telescopic feeder, and the charging deck where a hopper operates; the preheating chamber is installed beside the EAF upper shell and the preheated scrap is charged continuously by the telescopic feeder system into EAF for melting [10].

Table 1
Current technologies for energy recovery from EAF off-gas.

Energy recovery	Charge	Technology	Reference
Direct (scrap preheating)	Discontinuous	Shaft furnaces	[5]
		Twin-shell	[6]
	Continuous	Consteel	[7,8]
		Ecoarc	[9]
		EPC system	[10]
Indirect (steam production)	N/A	SMS Siemag AG	[14]
		iRecovery (Lv. 1)	[15]
		iRecovery (Lv.2)	[16]
		Simetal EAF Quantum	[17]

In spite of significant advantages [11], such as the reduction of the tap-to-tap (TTT) cycle time, the decrease of power requirements, and the reduction of CO_2 emissions [12] 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, and high emission factors for dioxins [13].

In indirect recovery, off-gas thermal energy is carried out by a HTF, such as steam or molten salt. Systems based on steam flowing through the cooling pipes of the off-gas ducts are SMS Siemag AG [14] and iRecovery Level 1 [15]; iRecovery Level 2 technology [16] adds a waste heat boiler located downstream the off-gas ducts. For what concerns the use of molten salt, a pilot project installed in a Simetal EAF Quantum employs molten salts as heat transfer and storage media [17].

There are several applications where the recovered heat by the HTF can be used downstream, such as district heating, vacuum degasser, and power production [16]. However, as underlined in [18], due to off-gas variability, thermal energy storage (TES) is necessary to provide the downstream systems with a constant supply of thermal energy.

Besides the traditional sensible energy storage, innovative TES systems are based on latent heat storage (LHS) technologies that exploit PCMs to store energy as latent heat and release it at a