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Comparison of electric arc furnace dust treatment technologies using exergy efficiency

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A B S T R A C T

Multiple methods exist to treat electric arc furnace dust (EAFD), aiming at high metal recovery and low landfilling needs. However, a technology that is energy efficient and recovers both Zn and Fe has only recently been developed to a commercial scale with the Rotary Hearth Furnace. Various other technologies have been proposed as alternatives to the historically preferred Waelz Kiln process. This gate-to-gate study presents an objective method to compare the overall thermodynamic performance and efficiency of treatment technologies through the use of an exergy analysis incorporating the dominant factors without the need of examining every process detail. In addition, the influence of the EAFD zinc content on the exergy efficiency of both the Waelz Kiln and Rotary Hearth Furnace process was studied. The efficiencies of these high temperature metal recovery processes were also compared to the efficiency of the newly proposed In-Process Separation technology.

1. Introduction

During the melting of steel scrap in an electric arc furnace (EAF), around 11–20 kg of dust (EAFD) is formed for each ton of produced steel (Liebman, 2000). This dust, which is rich in Fe and Zn oxides, was classified as a hazardous waste in the late 1980s by the Environmental Protection Agency (EPA), because it contains leachable Cd, Pb, and Cr(VI) (Assis, 1998). It is also listed as a hazardous waste in the European Waste Catalog, which means that disposal of untreated dust through landfilling is forbidden both in the United States and Europe (Assis, 1998; EPA, 2002).

The quality of the scrap that is melted in the EAF predominantly determines the composition of the generated dust. Typical compositional ranges for EAFD are given in Table 1.

As can be seen in Table 2, it was estimated that in 2009 almost 6 Mt of EAF dust was generated worldwide. From this, 2.5 Mt was actually recycled, while the rest was landfilled. For Zn, this results in a recovery of 588 kt of a possible total of 1333 kt when an average Zn content of 23 wt% is assumed for EAFD. Also, 1738 kt of FeO is present in the dust, assuming 30 wt% FeO, from which only a very small fraction is recycled. Even though a lot of effort has been invested in the development of new recycling techniques, 80% of all the recycled dust is still treated with the Waelz Kiln technique, followed by a much smaller fraction that is treated by the Rotary Hearth Furnace (RHF).

Table 2 also shows that both North America and Europe are already recycling large amounts of dust both from their own iron production and from that of neighboring regions. This import results in a recycling percentage larger than 100%. In the rest of the world, the recycling capacity is limited, but this is expected to increase significantly in the coming years. One example of this is the construction of new RHF recycling plant units in South Korea. However, in a world where both energy and resources are becoming increasingly scarce, with rising prices as a result, an industrial ecology study with a focus on sustainability is recommended before new installations are built.

Despite providing less information than a traditional Life Cycle Assessment (LCA), exergy analysis offers a very applicable and valuable method to study processes in the light of sustainable resource use (Amini et al., 2007; Castro et al., 2007; Ometto and Roma, 2010; Seager and Theis, 2002) and as such has been used as an integral part of some recent LCA studies in a variety of fields (Huysveld et al., 2013; Peiró et al., 2010; Valderrama et al., 2012). An exergy balance of a process is helpful to understand the effect of different parameters on the process efficiency and to determine the most effective processing conditions starting from objective thermodynamic principles and data (Szargut et al., 1988).

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Nomenclature

η	efficiency
B	exergy, J
g	the amount of carbothermal reduction gas returned to the solid fraction
m	mass, g
$x\%$	the amount of the internal process stream transported to the gas reoxidation reaction

Subscript

B	based on an exergy balance
ext, int, tot	indicator of the type of efficiency; external (ext), internal (int), and total (tot)

Abbreviations

DRI	directly reduced iron
EAF	electric arc furnace
EAFD	electric arc furnace dust
EPA	environmental protection agency
EU27	European Union (27 member states)
HBI	hot briquetted iron
LCA	life cycle assessment
NAFTA	North American Free Trade Agreement
IPS	in-process separation
RHF	rotary hearth furnace
SD	synthetic dusts
SEASI	South East Asia Iron & Steel Institute

In this gate-to-gate study, an exergy analysis has been performed to compare the widely used Waelz Kiln process with the newer RHF process for the recycling of EAFD. The variables were the different operational modes of the processes, the amount of Zn (wt %) in the treated dust, different product qualities for the RHF process, and the inclusion of the Waelz Slag as a useful product.

The Waelz Kiln process became the most widely used process mainly because it was the first process to be recognized as a proven and Best Available Technology in Europe for recycling EAFD with high zinc content (European Commission, 2001). Until recently, the RHF process was only suited for recycling EAFD with low zinc content (<5 wt%), but the technology has been reengineered to overcome operational problems such as ZnO blockages at higher zinc content (Nakayama and Taniishi, 2011). With the RHF process a higher grade zinc product and a directly reduced iron product (DRI) instead of a slag product may be produced and therefore it is claimed that this process is commercially and environmentally superior to the Waelz Kiln technology (Nakayama and Taniishi, 2011; ZincOx, 2010). However, an extensive review on the performance of RHF operations, including the latest efforts, questions these claims (Piret, 2012).

1.1. Waelz Kiln

The process flow sheet of the Waelz Kiln process is shown in Fig. 1, showing both the old and the optimized operational mode. The process is based on the carbothermal reduction of zinc and iron oxides ($ZnO(s) + CO(g) \rightarrow Zn(g) + CO_2(g)$ and $Fe_2O_3(s) + 3CO(g) \rightarrow Fe(s) + 3CO_3(g)$) in a rotating kiln up to a temperature of 1200 °C. The EAFD is mixed with coke and a slag forming agent (silica or lime) and fed to the kiln. The coke reduces the EAFD, forcing the volatile elements such as Zn, Pb, and Cd along with halides to evaporate. The kiln is mostly heated by the reoxidation of the zinc vapor ($Zn(g) + ½O_2(g) \rightarrow ZnO(s)$) and the combustion of excess CO gas ($CO(g) + ½O_2(g) \rightarrow CO_2(g)$). Extra heat can be provided by burning natural gas through a flame lance. This is the major secondary source of heat for the traditional Waelz Kiln process, but only of minor importance for the optimized Waelz process. The latter uses air to oxidize the slag by injecting it in the bottom of the kiln. The oxygen in the air will reoxidize the reduced slag, generating additional heat. Most of the coke that did not react in the kiln is also oxidized to CO and CO_2 gas (Rütten et al., 2011).

The final products from this process are the so called Waelz Oxide, a zinc rich product that can be sold to zinc smelters, and an iron rich slag called the Waelz Slag. The Waelz Slag is treated to recover the unused coke fraction for reuse in the process. For the optimized process, the amount of this recovered coke fraction can be reduced to zero. The slag was previously used as a material for road construction and cement production. However, new regulations for the cement industry prohibit further use of the Waelz Slag in cement. As a result, most of the slag is now stockpiled, landfilled or returned to the EAF (Nakajima et al., 2008).

1.2. RHF

The recycling of EAFD with a RHF uses a similar carbothermal reduction reaction as the Waelz Kiln process, but the furnace is operated at the higher temperature of 1300 °C and uses coal instead of coke as a reducing agent. The process flow sheet is shown in Fig. 2. The EAFD is mixed with the coal and an organic binder and is pressed into pellets or briquettes. Compared to the Waelz Kiln process, the elimination of fine particles moving freely around in the furnace prevents most of the contamination of the zinc product with iron. The higher temperature results in a faster, more complete reaction and in a better zinc recovery (Tateishi et al., 2008).

Since no slag forming agent has to be added, the briquettes leave the furnace in the form of DRI instead of an iron rich slag. In the final section of the RHF, the DRI is removed from the furnace from where it can be further processed in multiple ways (Oda et al., 2006; Tateishi et al., 2008). It can be briquetted again, decreasing the surface of the iron to protect it from oxidation while it is

Table 2
EAF dust generation and recycling in 2009, based on Rütten et al. (2011).

	NAFTA	SEAISI	PR China	EU27	Other area	World
EAF steel (Mt)	50.7	64.3	48.3	60.3	118.3	341.8
EAF dust (kt)	760	1157	724	1024	2129	5795
Rec. EAFD (kt)	810	427	n.a.	1071	250	2558
Waelz Kiln	735	270		831	210	2046
RHF	25	62		40	20	147
Other	30	95		200	20	345
Rec. EAFD (%)	106.6	36.9	n.a.	104.5	11.7	44.1
Zinc recovery (kt)	186	98	n.a.	246	58	588

Table 1
Average EAFD composition (Rütten et al., 2011).

	Zn	Pb	Cd	Cl	F	Na_2O	K_2O	C	FeO	SiO_2	CaO	Hg
(wt%)	14–35	2–8	0.1–0.2	1–5	0.2–0.5	1.5–2.0	1.0–1.5	1–5	20–45	3–6	3–10	1–5 ppm