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Energy–environment–economy evaluations of commercial scale systems for blast furnace slag treatment: Dry slag granulation vs. water quenching

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HIGHLIGHTS

- A prototype dry slag granulation system was proposed and designed in commercial scale.
- The input and output flows of each slag-treatment system were identified.
- Life cycle assessment on the dry slag granulation method and water quenching methods was carried out.
- Economic costs and returns during the lifetime of slag were calculated.

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ABSTRACT

The high-temperature blast furnace slag is conventionally treated by water quenching (WQ) method with enormous waste heat unrecovered. To address this issue, dry slag granulation (DSG) technology has been proposed to recover the waste heat from molten slag. Before commercial implementation, the sustainability and feasibility of the DSG should be well assessed. In this study, life cycle assessment (LCA) is conducted on a designed DSG prototype system in commercial scale. The environmental sustainability and economic benefit of DSG are evaluated and compared with the WQ systems. The LCA results reveal that the DSG can potentially reduce the energy and resource consumptions by 150 kg-coal-eq/t-slag and 1547 kg/t-slag, respectively. The analysis on environment impact also clarifies that the DSG is an environmentally friendly method for slag treatment. Furthermore, the DSG method represents a possibility to recover the heat from high-temperature blast furnace slag and turn it into a valuable material with a profit of 92.9$/t-slag.

1. Introduction

The latest Adoption of Paris Agreement claimed the global response to the climate change by keeping the temperature increase below 2 °C [1]. To this end, a significant reduction in carbon dioxide emission is required, potentially resulting in more stringent emission standard on industries. As one of the most energy-and carbon-intensive industries, iron and steel manufacturing faces more grand challenge and thus has great motivation to develop and implement low carbon emission technologies [2]. One of the effective routes is to develop high-temperature waste heat recovery technologies [3]. It was estimated that about 20–50% input energy was lost as waste heat in the form of off-gas, molten slag, cooling water, etc. [4]. In the past decades, some advanced technologies, for example, top gas recovery turbine unit (TRT), coke dry quenching (CDQ) and LT-Purification and recovery (LT-PR) of converter gas, have been developed to recover heat from off-gas, which lower the energy consumption and waste emission [5,6]. However, blast furnace slag (BFS) with a large amount of heat more than 2000 TJ/year has still been untapped [7], representing an possibility of further energy conservation in the iron and steel industries [8].

Nowadays, the BFS is usually treated by water quenching (WQ) methods including the open circuit process (OCP) [9], INBA [10], TYNA [11], RASA [12], etc. During water quenching process, high-pressure water is employed to shatter the molten slag. However, the water quenching methods not only fail to recover the high-temperature waste heat but also consume a huge amount of fresh water by the evaporation of 1000–1500 l of water per ton of slag [13].

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As an alternative sustainable technology, dry slag granulation (DSG) with air as the cooling medium was proposed to recover the sensible heat and to reduce freshwater consumption by Berger in 1930 [14]. Since it was coined, various DSG techniques such as rotary drum [15], air blast [16] and centrifugal granulation [17,18] have been developed for slag treatment. In terms of the desirable simplicity, reliability and efficiency of equipment, the centrifugal granulation has been regarded as the most promising DSG technique to deal with the molten slag.

The original centrifugal granulation system consisted of two successive fluidized beds, which was firstly designed by Pickering [19] in 1985. Conceptually, this DSG technology mainly involved two strategies: (1) slag granulation and (2) heat exchange. Good granulation producing small particles with high surface-to-volume ratio is crucially important for successful heat recovery. Mizuochi and his co-workers [17] investigated the influence of operating conditions on particle size. Another work by Mizuochi et al. [20] found that the vaned-atomizer inhibited the generation of large particles. Yu et al. [21–24] experimentally studied the centrifugal granulation mechanism of molten slag and the results showed that ligament formation was preferable for slag particle production. More recently, Zhu et al. [25,26] reported the mechanism of fibers formation during centrifugal granulation. With respect to the heat exchange of molten slag, the key challenge is to develop heat exchanger with high heat recovery efficiency and fast cooling rate of slag particles for high glassy production. Yu et al. [27,28] reported a tubular heat exchanger to produce hot water, whose the heat recovery rate ranged from 40% to 90%. Later, their works involved the glassy content inside slag particles [29]. Up to date, Commonwealth Scientific and Industrial Research Organization (CSIRO, Australia) has achieved outstanding progress in heat recovery, covering the design, development and scale-up of DSG in 2002 [30]. Based on their two-step conception, the slag can be cooled down to about 50 °C with hot air up to 600 °C.

So far, despite the significant progress in DSG has been made, most of the researches are focused on the innovation of apparatus design and technical process as well as the optimization of operational conditions at laboratory scale, and the scaled-up commercial is still hardly to see. No works has been reported on the systematical estimation of the DSG technology and its advantages over WQ technique. Doubts still remain about the feasibility of DSG in commercial application for slag treatment. Therefore, a systematically and comprehensive evaluation is an indispensable and prerequisite mission for promoting the development and application of DSG technology and reducing the risk of scale-up failures.

Harry E. Teasley firstly conceived a resource and environment profile analysis to manage package functions for The Coca Cola Company in 1969 [31]. The promoted analytical scheme was then developed into the world-famous life cycle assessment with the consistent efforts by Society of Environmental Toxicology and Chemistry (SETAC) [32]. It served as a tool to assess resource consumption and environmental impacts throughout the product's lifetime [33]. This approach has been well applied to evaluate the environmental sustainability and economic affordability of various scenarios such as passenger vehicles [34], buildings [35], hydrogen production [36], and biofuels [37]. Equally important, of great interests is the discrepancy in environmental impacts and economic cost of blast furnace slag treated differently. From the life-cycle perspective of BFS, the implementation of WQ method for slag treatment involves with fresh water, electricity and coal [38]. While the DSG method only related to electricity consumption caused by the usage of granulator and fans. Therefore, a trade-off analysis between DSG and WQ methods is indispensable.

The aim of present work is to implement the life cycle assessment (LCA) on the sustainability of DSG technology and thus provide a consolidated proof for the feasibility of DSG system. The centrifugal-granulation-based DSG system is designed in commercial scale based on existing research results and then the environment impact and economic benefits are identified. Meanwhile, a comprehensive comparison between DSG and the existed WQ methods is made to enable the selection of the optimal slag-treatment method.

2. System description

In this study, the LCA is performed to analyze the sustainability of two types of slag treatment methods i.e. DSG and WQ. The sustainability in this study is related to energy consumption, resource consumption, environment emission and economy. The WQ systems (including OCP, INBA, TYNA, and RASA) are mature in industrial application. The process of slag treatment by WQ systems is depicted principally in Fig. 1a. It involves the slag granulation by high-pressure water, slag splitter from water, slag transmission and slag drying. The WQ systems are well commercialized and adopted to treat slag worldwide. On the contrary, the DSG system is still at the stage of research. To bridge the gap between WQ in commercial scale and DSG in laboratorial scale, a prototype DSG system is proposed based on three-step process (Fig. 1b). In the first stage, the slag is transmitted into the storage silo and then distributed into several granulating apparatuses that meets the slag capacity of local iron and steel company. The slag is granulated into small particles and finally cooled down below 1300 °C during flight. In the second step, the slag is then charged into a fluidized bed where the air cools the slag down to 800 °C. In the final step, the slag is continuously cooled down to 100 °C, which is used as the feedstock for cement production eventually. Especially, as the commercial scale DSG system is designed through theoretical calculation, some assumptions were made including:

(1) Slag granules diameters are within 2 mm.
(2) Final granules produced by DSG have the same glassy content with that produced by WQ methods.
(3) Heat loss from slag granules is ignorable.

Table 1 shows the detailed operational parameters of the DSG system. One can find that this system is designed with capability of treating slag at a rate up to 18 t/h (or 5 kg/s). A disc atomizer with 1.2 mm in diameter is utilized [40] and the granulating chamber is 3.2 m in diameter to assure that the slag particles surface solidify before impacting on the wall of chamber [41]. During the operation in quasi-steady state, the rotary speed maintains at 2000 rpm, and the resulted electricity is calculated as 500 W [42]. The flowrates of cool air at ambient for fluidized bed and spouted bed are 5.699 m^3/s and 5.739 m^3/s, respectively. The corresponding power consumptions are 49.0 kW and 41.2 kW with fan efficiency about 81.5% and 80.5% accordingly.

3. Life cycle assessment

Life cycle assessment expands the key social actors' responsibility to include environment, economy implications during the entire life cycle of product, process and system [43]. It involves the cradle-to-grave analysis, which helps identify the evident impacts on environment for different process. And it enables policy makers or social actors to figure out the optimum process, as well as possible improvement.

Generally, midpoint and endpoint methodologies are available for LCA implementing. Herein, midpoint methodology is more suitable for present study because of its capability to demonstrate DSG's sustainability in more specific environmental categories. Thus CML 2001 method is chosen to perform the assessment. Addi-