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Exergetic life cycle assessment of cement production process with waste heat power generation

Xiuwen Sui [a], Yun Zhang [a,*], Shuai Shao [a,b], Shushen Zhang [a]

[a] Key Laboratory of Industrial Ecology and Environmental Engineering (MOE), School of Environmental Science and Technology, Dalian University of Technology, Dalian 116024, China
[b] School of Innovation Experiment, Dalian University of Technology, Dalian 116024, China

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A B S T R A C T

The cement industry is an industry that consumes a considerable quantity of resources and energy and has a very large influence on the efficient use of global resources and energy. In this study, exergetic life cycle assessment is performed for the cement production process, and the energy efficiency and exergy efficiency of each system before and after waste heat power generation is investigated. The study indicates that, before carrying out a waste heat power generation project, the objective energy efficiencies of the raw material preparation system, pulverized coal preparation system and rotary kiln system are 39.4%, 10.8% and 50.2%, respectively, and the objective exergy efficiencies are 4.5%, 1.4% and 33.7%, respectively; after carrying out a waste heat power generation project, the objective energy efficiencies are 45.8%, 15.5% and 55.1%, respectively, and the objective exergy efficiencies are 7.8%, 2.8% and 38.1%, respectively. The waste heat power generation project can recover 3.7% of the total input exergy of a rotary kiln system and improve the objective exergy efficiencies of the above three systems. The study can identify degree of resource and energy utilization and the energy-saving effect of a waste heat power generation project on each system, and provide technical support for managers in the implementation of energy-saving schemes.

1. Introduction

Cement is a basic raw material of a national economy, and the cement industry plays an important role not only in China but also in the global economy. Since 1985, China has become the world's largest cement producer, with a cement yield reaching 2.21 billion tons in 2012, a 5.3% increase compared with 2011 [1]. Cement production includes raw material preparation, pulverized coal preparation, clinker calcination, cement grinding and other related processes, and it is an industry with typical high resource and energy consumption and heavy pollution. From the viewpoint of resource and energy consumption, cement production consumes a considerable quantity of natural resources as raw materials for production, such as limestone, clay, gypsum and other auxiliary materials. In China cement industry, coal is the main fuel. So, in addition, it consumes large amounts of coal and electricity. Coal is mainly used for the clinker calcination link, whereas electricity is required in all stages of production, though electricity is mainly used for the rotary kiln, crushing, grinding, transportation and the use of other necessary electric equipment. According to data, producing a ton of cement will consume approximately 1.1 tons of limestone, 0.18 tons of clay, 0.1 tons of standard coal and 110 kW h of electricity [2,3]. Among all the links in cement production, clinker calcination is the most complex and is the stage with the highest energy, as it involves not only a conventional thermal process of energy transfer but also the decomposition of raw material, solid phase reaction, liquid phase sintering, clinker cooling and a series of other complicated physical and chemical changes, and they all consume large amounts of heat. The energy consumption during the cement production process mainly includes the following three parts: the thermal energy required for drying raw material and fuel, the electricity used for equipment operation and the thermal energy for clinker calcination.

Exergy analysis which is based on the first and second law of thermodynamics and uses exergy balance as a tool, it can overcome the deficiency of energy analysis, and evaluate the thermodynamic perfection of energy systems or energy-using equipment and reveal the energy quality disintegration rule during energy transfer and conversion [4,5]. As a modern thermodynamic method and an advanced tool in the industrial process, exergy analysis not only provides alternative views for accurate evaluation based on energy but also can diagnose the type of heat losses, the location and the quantity.

* Corresponding author. Tel./fax: +86 411 8470 6151.
E-mail address: zhangyun@dlut.edu.cn (Y. Zhang).

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The efficient use of energy is the focus of attention all over the world. In recent years, performing both energy analysis and exergy analysis for energy utilization in the field of cement production has become a research direction of interest for industry experts. Utlu et al. [6] used actual operational data to perform energy and exergy analysis of a raw mill and found the main heat losses by calculation. Söğüt et al. [7] investigated a coal-preparation unit in a cement plant from the perspective of exergy and aimed to examine the effect of varying dead state temperatures on exergy efficiency, and the study also considered exergy depletion, potential improvement and the effects of CO_2 emissions from different fuels. Sogut et al. [8] assessed the performance of a trass mill in a cement plant using an energy and exergy analysis method. Camdali et al. [9] applied energy and exergy analysis to examine a dry system rotary burner with pre-calcinations and performed a comparison with the efficiencies of the first and second law of thermodynamics. Kolip [10] performed energy and exergy analyses to investigate the whole system of a rotary burner with a four-cyclone-stage precalciner and four subsystems including a pre-heater, calciner, rotary burner and clinker cooling, and calculated the irreversibility of each subsystem and diagnosed the factors that caused the largest irreversibility. Karellas et al. [11] performed energetic and exergetic analysis for two different waste heat recovery systems in the cement industry. Atmaca and Yumrutaş [12,13] performed exergy and exergoeconomic analysis for a Turkey cement plant, and investigated the overall of energy efficiency and exergy efficiency of the plant and calculated the specific unit exergetic and manufacturing costs of the farine, clinker and cement. Renó et al. [14] assessed the cement production which applying waste fuel and mineralizer from an exergetic viewpoint and aimed to identify the advantages of the application of waste spent pot lining as a mineralizer in clinker production. The researches in the cement industry are mainly focused on the exergy analysis of cement kiln. There is only a relatively small amount of research investigating the exergy of raw mills, coal mills and other equipment. These studies are aimed at particular equipment or systems in cement production, and studies of the entire cement production process are infrequent.

Exergetic life cycle assessment (ELCA) uses the framework of life cycle assessment (LCA) and can be considered as the exergy analysis of the whole life cycle [15]. It is a methodology that integrates LCA and exergy analysis, and it runs through the whole life cycle from cradle to grave. ELCA can investigate the resource consumption, energy utilization and environment impact of the systems or processes. ELCA, which is based on the second law of thermodynamics and treats exergy as a basic physical parameter, evaluates the whole system comprehensively in terms of both "quantity" and "quality" and accurately locates the position that irreversibility occurs.

At present, ELCA has been used in different industries and fields, such as hydrogen production, waste aluminum treatment, resource consumption in a built environment, biodiesel production, Pangasius aquaculture, cane sugar production, biorefinery and semi-closed gas turbine cycle [16–24]. These studies have demonstrated that ELCA is a practical tool that is used to investigate the resource and energy utilization and the environmental impact of emissions in all stages of the system life cycle. LCA has many difficulties when used for comparison with different energy forms because LCA is based on the first of thermodynamics. However, ELCA can avoid these problems. Compared with conventional exergy analysis, ELCA extends the scope of application to every aspect of the system life cycle. For this reason, applying ELCA to evaluate products or processes is more comprehensive and exact. However, there is almost no study which applies ELCA theory for cement industry especially in China. Not to mention the energy efficiency and exergy efficiency of each system before and after waste heat power generation are compared. In this study, the energy utilization analysis of cement production process is performed with the assistance of ELCA.

In China, the energy consumption for cement production accounts for approximately 7–8% of the national energy production, and 70–80% of the energy is consumed by clinker formation [25]. Therefore, energy consumption minimization and energy utilization efficiency maximization has become a hot topic among cement industry experts. It is urgent to assess the energy utilization of China cement industry, meanwhile, it is infrequent to perform ELCA for the whole cement production process especially in China. The study will provide accurate data of the energy utilization of China cement industry and the effect of waste heat power generation project for each production system. Not only the study possess reference value for readers to research the application of ELCA in cement industry, but also it provides data support for cement industry experts. In this study, using the actual production data of a China case cement plant and the viewpoint of thermodynamics to perform exergetic life cycle assessment of the cement production process, the energy efficiency and exergy efficiency of each system in the cement production process is investigated, and the efficiency of each system before and after waste heat power generation is analyzed. Using the results of these analyses, the degree of resource and energy utilization and the energy-saving effect of a waste heat power generation project for each system can be determined.

2. Methodology

2.1. Exergetic life cycle assessment

The framework of ELCA is similar to the definition of LCA in ISO14040 and 14044 [26,27], and it is divided into four stages as shown in Fig. 1. The four stages of ELCA in this study and the differences with LCA are introduced as follows [28].

(1) The goal and scope definition of ELCA is identical to that of LCA. In this study, although the cement production of the case plant includes a raw material preparation system, pulverized coal preparation system, rotary kiln system and cement production system, those systems closely related to cement clinker production are considered, namely the study's system boundary is the raw material preparation system, pulverized coal preparation system and rotary kiln

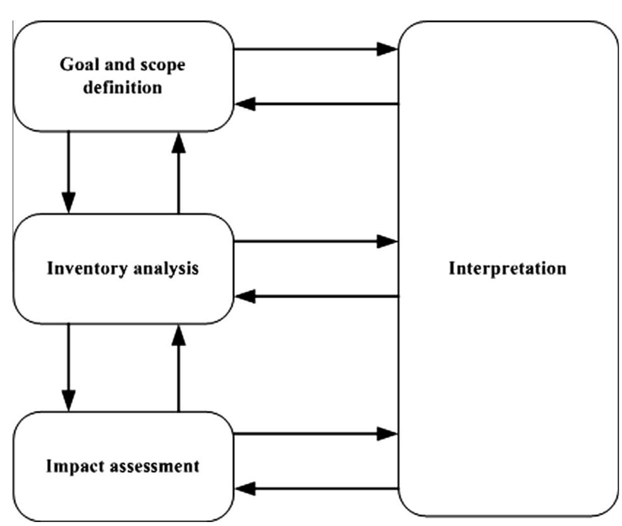

Fig. 1. The ELCA framework.