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Analyzing thermodynamic improvement potential of a selected cement manufacturing process: Advanced exergy analysis

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ABSTRACT

Cement industry uses very energy-intensive operations resulting in a suboptimal sustainable performance. The objective of this research is to provide insight into the value of exergy analysis in sustainability assessment of cement industry. For that purpose, a detailed exergy evaluation of a complete cement plant located in Morocco was performed using both conventional and advanced exergetic analysis. The major internal exergy losses were identified during the calcination process and the two raw mill departments, which amounts to about 78.66%, 70.86%, and 72.12% respectively. Those irreversibilities are split into avoidable/unavoidable exergy destruction in the advanced exergy analysis. Findings show that 15%, 29.21% and 31.54% of the total exergy destruction in the calciner and the raw mills 1 and 2 respectively are avoidable. However, there is a need for optimization of comminution and combustion operating parameters in the cement production process currently in use.

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1. Introduction

High energy intensity puts the cement industry under pressure from both an environmental and economic point of view. The industry operates at about 54% thermal efficiency [1,2,3]. This inevitably means that huge amounts of the resources used in cement production are used in vain, and that the greenhouse gas emissions caused by production of cement that gets lost or wasted are also emissions in vain. The large losses should be seen not as an insurmountable obstacle but as a challenge to achieve technical improvements [4]. Thermodynamics offers a great help in studying sustainable development due to its wide applicability in all fields of science and engineering. The exergy concept particularly needs to be evaluated and eventually be confirmed through practical experience. In doing so, exergy method is used in this study to analyze a cement processing facility, which is one of the largest energy consumers within the cement industry in Morocco. While a conventional energy analysis maps the energy flows of the system and suggests opportunities for process integration [2], a detailed exergy analysis pinpoints the locations, causes and magnitudes of thermodynamic losses [5]. By applying this methodology to the energy-intensive cement production, inefficiencies and potential improvements are to be detected with the aim to develop towards a more sustainable system. In this study, both exergy efficiency and exergy destruction are analyzed and evaluated for that purpose. Conducting research projects in this field can serve as a reference to calculate exergy values that are not being effectively shared among the research community yet. Such research projects also provide useful information to the managers and decision makers for prioritizing the potential improvements and developing strategies for system performance enhancement [6].

Many books published over the recent years have been based on the concept of exergy (**Enrique et al.** [7], **Silvio** [8], **Dincer** [9], **Bejan** [10], **Dincer** [11]), many conference reports (**Rashad et al.** [12], **Bühler et al.** [13], **Bühler et al.** [14]) as well as a significant number of studies have been published in the exergy field. Among them, there are very important and deductive papers. **Camdali et al.** [15] indicated that the first law of thermodynamics, which is used to increase the energy recovery and decrease losses, is not enough to establish a detailed energy management scheme for the cement industry. Traditionally exergy analysis has been applied mainly to single processes or applications. **Utlu et al.** [16] performed an energy and exergy analysis of a raw mill in a cement production plant. According to their study, the energy and exergy efficiencies are determined to be 84.3% and 25.2%, respectively. **Atmaca and Kanoğlu** [17] also studied the raw mill in cement

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industry. They evaluated the specific energy consumption for farine production to be 24.75 kWh/ton farine. By using an external hot gas supply, the energy consumption of the unit has been reduced by 6.7% corresponding to a saving of 1.66 kWh/ton of farine production. The trass mill in a cement production plant has been investigated in relation to exergy analysis. The objective of **Söğüt et al.** [18] was to perform an energetic and exergetic assessment of a trass mill process in a cement plant, the overall exergy efficiencies are found to be slightly less than the corresponding energy efficiencies 74% and 10.68% for energy and exergy efficiency, respectively. **Söğüt et al.** [19] investigated the energy and exergy analyses of a coal-preparation unit in a cement plant. The mean values of energy and exergy efficiencies of the unit are found to be 74.03% and 21.36%, respectively while the average potential improvement of the unit is calculated as 78.24%. In **Madlool et al.'s** [20] work a review of the exergy analysis was presented to demonstrate that the implementation of exergy analysis on the cement production line is a very efficient way to improve the performance of the system. Although **Savaş et al.** [21] presented comparative energy and exergy analyses for specific dry clinker production by three different methods, they concluded that the lowest irreversibility rate occurs in the serial flow pre-calcination cement production method. The work of **Bühler et al.** [22] consists of analyzing the energy and exergy efficiency, as well as the destroyed and lost exergy of 22 industrial sectors in Denmark for the years 2006 and 2012. They concluded that industries with high temperature processes such as cement production achieve the highest efficiencies. **Koroneos et al.** [23] examined the efforts to improve energy efficiency in cement production in Greece using exergy analysis. The analysis includes calculation of energy and exergy contribution at each stage of the cement manufacturing procedure. They found that about 50% of the exergy is being lost while substantial amount of waste heat is being recovered. In a study led by **Ahamed et al.** [24] and **Atmaca and Yumrutaş** [25] the first and second law efficiencies of a clinker cooler were calculated. The study of [24] showed that about 38% and 30% of energy cost can be saved by changing mass flow rate of clinker and mass flow rate of cooling air, respectively. **Atmaca et al.** [1] and **Atmaca and Yumrutaş** [26] revealed interesting results in exergy analysis of the kiln system. In Ref. [1] they reduced the rate of heat loss from 22.7 MW to 17.3 MW by the application of insulation to the pyroprocessing unit of Gaziantep cement plant in Turkey. They calculated that 1056.7 kW of electricity can be generated by using the waste heat and reduced the annual emission rates by 8.2%.

Inefficiencies in an energy system can be quantitatively determined through conventional exergy analysis; while sources of the irreversibilities and real improvement potential can be deducted using a relatively new method named as advanced exergy analysis [27]. This later is applied to determine real potential for thermodynamic improvements of energy systems by splitting exergy destruction into unavoidable and avoidable portions. According to the current knowledge of the authors, until now no cement plant has been analyzed and evaluated using this method. However, its applications in other sectors are relatively low in numbers: **Tsatsaronis and Moung-Ho** [28] discussed how to estimate the avoidable-unavoidable exergy destruction. They evaluated parts of exergy destructions of compressors, turbines, heat exchangers and combustion chambers, which were used to determine the improvement potentials of a thermal system. **Morosuk et al.** [29] presented the theory of the conventional and advanced exergetic analyses. They concluded that the information resulted from the advanced exergy based method was very useful in developing approaches for improving the energy conversion systems. **Gungor et al.** [30] investigated the advanced exergy analysis to a gas engine heat pump dryer for medicinal and aromatic plants, evaluating its performance in parts and discussed possible structural improvements of the whole system and the remaining system components.

Results found in the open literature are not typically combined to give an overall representation of the cement industrial process from an exergy perspective. Almost no comminution exergy model has been proposed nor applied to a cement process in which comminution is carried out to produce material of controlled particle size [31]. The present work contributes to the current literature from several perspectives. A detailed exergy evaluation of a complete cement plant with all main units is performed using both conventional and advanced exergetic analysis. In one hand, with conventional exergy-based analysis, thermodynamic inefficiencies were assessed; the critical points were localized and information about improvements of the studied cement plant is revealed. Furthermore, exergetic ternary diagram as a new graphical representation of the exergy balances allows the immediate visualization of the results of exergy analysis and the comparison between the exergetic indicators (exergetic efficiency, irreversibility and exergy losses) of each operation unit making up the whole system. In the other hand, the advanced exergy analysis reveals the real potential for improvement of the unit with the highest exergy destruction ratio by calculating the amount of its avoidable part. Based on the findings, insights for improvement can be extracted.

Before detailing the advanced exergy analysis methodology and explaining the graphical representation used to illustrate efficiency, irreversibilities and external losses in section 3, a brief description of the cement-making process and data used is given. Section 4 discusses the main findings and provides guidance on the key considerations for the assessment of the system performance. Finally, section 5 concludes our analysis.

2. Process description of the plant production line

Cement production is a complex process which includes operations such as preparation of raw materials, clinker formation and cooling to achieve a crystallographic structure that meets the required cement specifications, and finish milling. For raw material preparation and cement grinding, the main energy carrier is electricity whilst the thermal energy is consumed in the calcination process of clinker manufacturing. In the present study, a Moroccan cement plant with 1.2 million tons as an annual production capacity is considered as a case study for the exergy analysis assessment. The plant required thermal energy inputs of 2.17 GJ/ton clinker and 0.36 GJ electricity/ton cement. The main flows entering or leaving the cement system boundary are summarized in Fig. 1. Furthermore, each department is defined and delimited by a boundary that cuts across all the streams and encloses each specific process, but not their sub-system.

The dry production process is used in the typical plant and it consists of grinding the mixture of raw materials (streams 8 and 24) which are manufactured through a closely controlled chemical combination of calcium, silicon, aluminum, iron and other ingredients to make a fine powder. The prepared raw meal (stream 37) is thus preheated in a four stage cyclone-type suspension preheater using the waste heat of the kiln (stream 47). The preheated raw mix powder and gases are separated in the cyclone by the centrifugal motion induced by the geometry of the cyclone, with the exhaust gases passing out of the top of the cyclone and the preheated raw mix passing out of the bottom of the cyclone to the next lower stage of the preheater. The plant owns an additional calcining vessel, in which the raw-mix undergoes calcination to a level of 90–95% [32]. This way, the preheated raw-mix (stream 44) enters the calciner together with the fuel and the hot tertiary air (stream 51). Calcining takes place at 800–900 °C and breaks the

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