Enhancing the Sustainability of Alumina Refineries: Exergy Insights from Process Simulation

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Abstract

The Bayer process is the dominant industrial method for alumina production, but it is highly energy-intensive, with significant thermodynamic inefficiencies and exergy losses occurring throughout the process. This study presents a simulation-based exergy analysis of a full-scale Bayer refinery, the key focus is on identifying the most exergy-intensive subprocesses, particularly in thermal and chemical exergy utilization. Beyond a base case analysis, scenario simulations are conducted by varying key process parameters to assess their impact on overall exergy efficiency and sustainability. This simulation-based approach enables a systematic evaluation of how process modifications can enhance energy efficiency, reduce waste heat losses, and improve the overall sustainability of alumina refining. The model's flexibility allows for its application across different refinery configurations, making it a valuable tool for optimizing alumina production in line with circular economy principles and also rigorously permits an allocation of impacts of all flows, products, residues etc.

Keywords: Bayer process, Exergy analysis, Sustainability, Process simulation, Energy efficiency.

1. Introduction

Developed in the 19th century, the Bayer process remains the predominant industrial method for alumina production worldwide, with more than 95 % of global alumina produced through this method [1]. Despite its robustness and industrial maturity, the Bayer process is notably energy intensive. Bayer process requires high-pressure steam for heating and combustion burners for the calcination of the hydrated alumina, both of which rely mainly on fossil fuel energy. Overall alumina refineries have a significant share of energy demand and contribute to the 1–2 % of the global greenhouse gas (GHG) emissions [2].

Sustainability efforts in the alumina sector have traditionally focused on energy reduction, residue management, and emissions control. Núñez and Jones [3], identified digestion and calcination as the most environmentally burdensome stages of the Bayer process, together accounting for more than 70 % of the process's total cumulative energy demand and global warming potential. Similarly, Guinoa et al. [2] disaggregated environmental impacts and demonstrated that calcination and digestion are responsible for up to 77 % of CO_2-equivalent emissions. In the specific refinery configuration modelled, which was based on natural gas combustion, fuel related emissions alone accounted for over 65 % of the total site emissions. Furthermore, bauxite mineralogy and transportation logistics emerge as critical sensitivity factors, with up to 51 % variance in emissions based solely on ore type and energy mix. While Life Cycle Assessments (LCAs) can provide valuable insights into the environmental impacts of alumina production, it does not explain the underlying thermodynamic causes of inefficiency and cannot pinpoint where improvements can be most effectively applied. On the other hand, exergy analysis, grounded in the second law of thermodynamics, offers a complementary perspective by quantifying the quality and usability of energy and material flows throughout a system. Unlike traditional energy accounting, exergy assessment distinguishes between useful work potential and irrecoverable losses, thus providing deeper insights into process inefficiencies [4]. This methodology has the potential to bridge gaps in environmental assessments by translating energy consumption into thermodynamic impact, thereby enabling more targeted strategies for improving sustainability. Exergy analysis evaluates the quality of energy and its degradation within a system, offering a complementary perspective to LCA.

In this study the exergy analysis is used to identify the inefficiencies in the Bayer process and assess how the process variations affect sustainability performance. A full-cycle Bayer simulation model is developed in the HSC Chemistry software. Initially a baseline model is calculated, to identify the major exergy demands of the Bayer process. A sensitivity analysis is also conducted for the digestion stage, where the effect of the digestion temperature and caustic addition is evaluated in terms of alumina extraction rate compared to exergy efficiency. The goal of this work, is to support more energy-efficient, lower-emission, and circular approaches within the alumina industry, aligning with broader goals of industrial decarbonization and resource optimization.

2. Methodology

2.1 Concept of Exergy Analysis

The concept of exergy analysis is based on the second law of thermodynamics, which states that in every real (irreversible) process a part of "the quality of the energy" is destroyed, meaning that the ability of the specific system to produce useful work is reduced. The useful part of the energy of the system, hence the part of energy that can be transformed into useful work (of any type), is defined as exergy [4].

An exergy analysis includes a detailed analysis of the energy and materials flows of the system/process under consideration, to identify the sources of exergy destruction and loss. In practice, an exergy analysis involves the identification and quantification of all input and output streams, as well as the determination of their exergy values using appropriate thermodynamic data. For any chemical process an exergy balance can be calculated using the Equation (1).

$$E_{input} = E_{useful\,products} + E_{output\,wastes} + E_{distruction} \quad (1)$$

In an exergy balance the input exergy (E_{input}) is always greater than the output exergy, which is the sum of the exergy values of the useful ($E_{useful\ products}$) and waste output (E_{wastes}) of the process, as a result of the second law of thermodynamics (2LT).

The calculation of exergy requires the use of reference environment conditions for the determination of the exergy potential of a substance or stream. Essentially, the exergy potential of a substance or a stream is the maximum amount of useful work that could be potentially released if the substance or stream reach thermodynamic equilibrium with the reference environment (dead state). Or vice versa, exergy potential is the minimum input work required for the production of the substance or stream from the reference environment. In processes where the external energy (kinetic and potential) is insignificant, the exergy of a substance or stream can be calculated by the sum of thermal and chemical exergy (Equation (2)) [4].

$$E_{stream,total} = E_{ph} + E_{ch} \quad (2)$$

These results validate exergy analysis as a critical complement to environmental assessments such as LCA. While LCA highlights impact hotspots, exergy reveals why those hotspots exist and where process-level improvements can be most effective. Overall, the work demonstrates that advancing the sustainability of alumina refining requires more than just reducing emissions or reagent use. It requires addressing the underlying thermodynamic drivers of inefficiency, and exergy analysis provides the framework to do that. The developed simulation model can be used as a diagnostic and optimization tool for existing refineries and can support the design of more circular, energy-efficient, and decarbonized alumina production systems.

5. References

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