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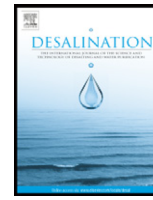

A comparative life cycle assessment of eutectic freeze crystallisation and evaporative crystallisation for the treatment of saline wastewater

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HIGHLIGHTS

► Two desalination techniques, EFC and EC, were compared by Life Cycle Assessment (LCA).
► EFC process is strongly preferred to EC for the modelled 4 wt.% Na_2SO_4 solution.
► EFC performs better for "global warming" and "non-renewable energy" impact categories.
► The environmental performance of EFC can be significantly reduced by heat integration.

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ABSTRACT

Two processes are compared by means of Life Cycle Assessment (LCA) to determine which one causes less environmental impact for the treatment of saline mining wastewater: Eutectic Freeze Crystallisation (EFC) or Evaporative Crystallisation (EC). EC is a well established technology whereas EFC is a new promising technology that has the potential to compete with EC but so far has not been built at industrial scale. As the processes yield by-product water in different states, system expansion was used to effect a fair comparison. The study considers three different geographical areas: South Africa, France and Europe, in order to identify the effect the source of energy has on the comparison. The energy efficiency of the chilling technology is studied parametrically. The LCA results show that for the modelled 4 wt.% sodium sulphate solution, the EFC process is strongly preferred to EC regardless of the country energy mix, requiring 6–7 times less energy resources, but also that process energy integration and chiller energy efficiency can further reduce its environmental impacts significantly.

1. Introduction

Increased water consumption is causing water scarcity problems in many countries, often exacerbated by discharges of polluted water. The mining industry is not exempt from these problems: whilst on a national scale it needs much less water than other sectors (especially agriculture or urban consumption), the local water demands and pollution potentials of a large mine relative to a small town and farming community are often considerable [1]. In response to water supply limitations, mines have increasingly started to treat and use mine water or to recover water from the tailings disposal facilities; such water is however often saline and can only be used after desalination. The resulting hyper-saline retentate poses disposal problems [2]. Evaporative crystallisation (EC) is an energy-intensive and expensive option sometimes used, producing either pure saleable salts or mixed salts to be disposed of as hazardous wastes [3].

Eutectic Freeze Crystallisation (EFC) has been proposed as an innovative technology to address these problems. Whilst EFC processes have thus far not been built at industrial scale, the technology is thought to be able to reclaim good quality water from mining wastewater whilst at the same time producing valuable products such as sodium sulphate or calcium sulphate [4]. Its energy consumption has been claimed to be significantly lower than that of alternative technology [3]. When deployed for the beneficiation of waste material, the process might thus be thought to be environmentally friendly or even 'sustainable'. Such claims of superior environmental performance should not be made without a rigorous environmental assessment.

Life Cycle Assessment (LCA) is a technique that can perform such environmental assessment since it is a "cradle-to-grave" approach. Recent case studies in which desalination technologies are compared by means of LCA include: a comparison of ion exchange and reverse osmosis [5], a comparison of reverse osmosis desalination using brackish groundwater or seawater [6], a comparison of three commercial desalination technologies (multistage flash, multi-effect evaporation and reverse osmosis) [7], a comparison of desalination technologies integrated

Abbreviations: EFC, eutectic freeze crystallisation; EC, evaporative crystallisation; LCA, life cycle assessment.

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with renewable energies (wind, photovoltaic and hydro-power energies) [8] and a comparison of desalination technologies with different energy production systems [9]. In these studies, the use of LCA enabled the identification of an environmentally superior technology (or feed for the same process).

This paper aims to present a comparative life cycle assessment of an EFC process and a common water treatment method used in the mining industry, namely that of EC.

2. Methods: goal and scope of the LCA

LCA is the methodology adopted in this study, as recommended by the International Standards Organization. As per the protocol in ISO 14040 [10], the goal of the study will first be stated, followed by a discussion of the scope. The document [11] has been used as a guide.

2.1. Goal

The goal of this study is to compare EFC, a technology under development, with a currently used multi-effect EC for the particular situation of separating solid salt from water. As discussed in the Introduction, this separation is becoming an increasingly used and needed step in the treatment of hyper-saline brines often associated with water circuits in the mining industry.

The two technologies have the potential to be used for the treatment of hyper-saline wastewater. In the present research, the comparison is performed on a feed brine that is made up of a single salt as the intention is to focus more on the technologies than on the behaviour of specific salts. The outcome of the comparison is primarily to be used to give direction to further technology development but also to make claims of relative environmental performance in specialist circles.

It is desirable to find out which process (EFC or EC) causes less environmental impact (quantifiably). As the material inputs and outputs will be the same in the two processes (i.e. no ancillary process chemicals are used in either process), the impact categories considered can be limited to those directly related to energy consumption only. These can be captured primarily by the indicator "depletion of non-renewable energy resources". Additionally, the indicators "global warming" and "ionizing radiation" can be used to compare emission-related impacts resulting from energy conversions. Whilst energy conversion results in a range of other impacts that are typically described by mid-point indicators such as "acidification", "eutrophication", "photochemical smog", "human toxicity" and "eco-toxicity", these are not considered here, as all of the mid-point indicators will essentially be calculated from only two major process energy requirements: electricity and heat.

The type of LCA adopted in this study is consequential, which investigates likely environmental consequences due to change in technology or processes [12,13]. The results of the study are meant to be used by:

(i) researchers in industrial wastewater treatment, especially those interested in technology innovation and in environmental sustainability research;
(ii) industrial wastewater decision makers; and
(iii) policy makers, industry, energy and environmental professionals or stakeholders, as well as implementers of wastewater treatment policies.

2.2. Scope

Two processes are considered and compared: a single EFC and an EC process consisting of three evaporative effects. The latest is an industrially frequently used arrangement. Since one of the processes is not yet industrially available, the comparison is informed by process modelling rather than by data of actual industrial performance.

The feed stream considered in the comparison represents what is called a hyper-saline wastewater in the mining industry: the intention is to completely separate water from the salts and recover both as resources. After examination of the compositions of several real multi-component industrial hyper-saline wastewaters [14] it was decided that the theoretical brine waste for this study should be simplified to one single salt which commonly appears in wastewater of the mining industry, viz. sodium sulphate. The concentration, 4 wt.%, was taken from one of the wastewaters studied in [14].

Mass and energy balance calculations were undertaken over the two process plants. The system boundary for the LCA analysis begins with the mass flowrate entry of 1000 metric ton/day hyper-saline wastewater, comprising sodium sulphate at 4 wt.%, to each process plant. The EFC process separates wastewater into salt and ice, however according to the thermodynamics of the process, the salt produced under eutectic conditions will be sodium sulphate decahydrated ($Na_2SO_4 \cdot 10H_2O$). Some of the product ice is used and melted in a heat exchanger in order to cool down the feed stream and also to save energy. The EC process separates water from the dehydrated salt and converts it into condensed steam. In order to compare both techniques by means of LCA, they need to deliver the same products.

Since anhydrous sodium sulphate is the more valuable form of the produced salt and ice is more valuable than water (from an energetic point of view), the system boundary ends when both processes produce anhydrous sodium sulphate and water in the same phase (see Fig. 1). The comparison of the two processes is achieved by the so-called "LCA system boundary expansion" [11]; in the case of EFC it will account for the production of dehydrated sodium sulphate from decahydrated sodium sulphate $Na_2SO_4 \cdot 10H_2O$, whilst the EC process will account for the production of ice from part of the liquid water (condensed steam).

2.2.1. Scenario development

Several scenarios are compared. Firstly, in the base case scenario, both processes are compared assuming that they are isolated, i.e. with no energy supply coming from other parts of the mother-plant. Since the wastewater treatment processes would generally be placed adjacent to the mother-plant, a case of energy integration is also explored. Also, the geographical context is considered in order to investigate the environmental performance of the two processes in different countries with varying energy mixes. The first setting investigated is South Africa, where mining industries have been reported to deal with hyper-saline wastewater streams [14]. As the South African energy mix is particularly carbon intensive, application of the two technologies in a country with a very different energy mix is also explored — France with its dominant nuclear electricity supply and access to natural gas for industrial heating was chosen. An average European energy mix is also explored. Finally, the efficiency of the chilling technology (reflective of its age) is varied.

2.3. Functional unit

The functional unit for the LCA investigation is the treatment of saline water to produce salt and water as shown in Fig. 1: a daily production of 40 ton of dehydrated sodium sulphate by each process and another 960 ton/day of "ice + liquid water" mixture in the amounts obtained by EFC.

2.4. Data quality

The particular EFC and EC processes considered here are hypothetical. Although there is some process data available from industrial application of EC, it was not used since i) it would be inconsistent to compare a general process (hypothetical EFC) with a specific one (real data of an EC process), and ii) in addition, there is often a