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Screening and cost assessment strategies for end-of-Pipe Zero Liquid Discharge systems

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ABSTRACT

Zero Liquid Discharge refers to the elimination of wastewater discharge from a process. Many Zero Liquid Discharge systems are designed to meet the increasingly stringent environmental regulations and enable water recovery. Generally speaking, a Zero Liquid Discharge process must be capable of minimizing produced wastewater volumes, by employing effective water treatment options. It is often crucial to ensure that effective combinations of treatment technologies are used to assemble a Zero Liquid Discharge system, in an economically feasible manner. Even though various recommendations for enhancing treatment systems involve minimizing wastewater generation, which would reduce the volume of wastewater treated all the way to Zero Liquid Discharge, it is often costly to retrofit existing wastewater generating systems, especially if large brine flowrates are involved. As a result, numerous brine-generating processes (such as desalination plants, textile plants etc.) employ end-of-pipe Zero Liquid Discharge systems, to meet strict environmental discharge standards. This paper aims to identify effective design strategies for End-of-Pipe Zero Liquid Discharge systems, by proposing an optimization approach that allows the screening through various treatment and Zero Liquid Discharge technologies, so as to assemble cost-effective Zero Liquid Discharge strategies and enable suitable water recovery options. The proposed model has been illustrated using a case study that demonstrates how the generated Zero Liquid Discharge scheme changes by varying the End-of-Pipe discharge requirements.

1. Introduction

Worldwide population growth and increasing water consumption have stressed existing water resources and rendered the need for sustainable water sources ever the more urgent (Subramani and Jacangelo, 2014). The challenge lies in the increasing demand for water while conventional supplies decrease. As such, alternative water resources are being sought to supplement the depleting natural water reserves; in particular, desalination technologies have gained much attention, as their capacities and performance have improved over the years (Morillo et al., 2014). Although on one hand, these technologies are producing potable water, on the other hand, they are producing concentrated waste streams, known as brine. Other industries also produce these waste brine streams, including textile, food, chemical, and salt production industries (Sharp et al., 2012). The characteristics of the brine produced depend on the feed entering the system and the technologies being employed (Perez-Gonzalez et al., 2012).

These brine streams constitute a growing industrial problem in terms of their disposal and associated environmental hazards. Disposal costs are high, and in the case of desalination technologies, can range between 5 and 35% of overall water costs (Gilron, 2016). These costs mainly depend on brine composition (treatment level prior to disposal), disposal method, and volume (Morillo et al., 2014). Brine discharge into the aquatic environment, poses a threat to the marine ecosystem and any living organisms within. This may be attributed to the brine's composition (mainly salinity and any residual chemical content following pretreatment), as well as the discharge temperature. Observed environmental impacts include eutrophication, pH variation, sterilizing properties, and the accumulation of harmful compounds (such as heavy metals) (Perez-Gonzalez et al., 2012).

Brine management strategies aim for brine minimization, direct brine disposal, or brine reuse (Gilron, 2016). The optimal option for brine disposal depends on a number of parameters such as: quantity of brine (volume), quality of brine (composition),

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geographic location (discharge point), and capital and operating costs (Giwa et al., 2017).

Common brine disposal options are: surface water discharge, dilution, deep well injection, and land application. Surface water disposal is advantageous in that it can accommodate large volumes, with low capital and operating costs and energy requirements (Masnoon and Glucina, 2011). However, it faces stringent environmental regulation and permit requirement (Subramani and Jacangelo, 2014) and often necessitates that the brine be pretreated, and that mixing zones be created in the water body. However, inland plants may not have access to suitable discharge points, rendering this option unfeasible (Mackey and Seacord, 2008). In this context, dilution consists of mixing/blending the brine with other municipal/industrial wastewater (Subramani and Jacangelo, 2014). Furthermore, deep well injection, which is a relatively cost-effective brine disposal technique with low energy requirements, releases the brine into subsurface rock formations and is suitable for inland plants. Nonetheless, it is only feasible in deep confined saline aquifers and non-seismic regions (Mackey and Seacord, 2008) as it carries the risk of groundwater contamination in addition to complex and detailed requirements for operation (Masnoon and Glucina, 2011). Land application refers to the technique that involves the use of the concentrate in the irrigation of crops with high salt-tolerance, which requires that the plant be near a fitting agricultural area, but, run-off of the concentrate to surface water and groundwater remains a major concern (Mackey and Seacord, 2008). As such, an effective long-term brine management strategy often entails the implementation of Zero Liquid Discharge (ZLD) technologies that could minimize/eliminate the discharge of brine volumes. Such systems were initially considered uneconomical by many industries, up until the introduction of economically viable options (Subramani and Jacangelo, 2014), which many industries opt for as an End-of-Pipe solution.

A number of studies have looked into the optimization of different water related systems, covering a wide range of different optimization methods. Trigueros et al. (2012) modeled and optimized water reuse networks by applying the Particle Swarm optimization method and introducing pinch analysis concepts that determine optimality on the basis on minimal freshwater flow rate, the number of interconnections, and the total cost of the network. Koleva et al. (2017) present two optimization based frameworks for the synthesis of water treatment processes to minimize water net cost; these frameworks combine different optimization techniques for improved results.

In addition, different studies have focused on different aspects of water networks and/or specific water resources for specific situations or systems. Alnouri and Linke (2012) introduced a systematic approach that can be used to develop an optimal membrane network for the desalination of seawater. In a later work, Alnouri et al. (2015) presented an optimization methodology that can be used in the cultivation of water integration networks in industrial cities. Alnouri et al. (2016) present a water network that considers both central and decentral treatment options in wastewater reuse and regeneration networks, while considering scenarios that merge pipelines accordingly, thus improving the cost of the network, instead of having a single pipeline for every water allocation move, which is more costly. Chauhan et al. (2016) looked into the optimization of brine treatment networks designed by integrating both membrane desalination technologies and salt production processes. Chaturvedi et al. (2016) studied the optimization of a schedule for the operation of batch water networks with multiple water networks for minimal operating cost; an interesting conclusion from the paper is that the same optimal schedule for networks with multiple water resources can be optimally applied to systems with a single water resource. Abdulbaki et al. (2017) developed an optimization model for water resource allocation (seawater, surface water, or wastewater) that satisfies water demand for particular use (irrigation, portable, or industrial) at the lowest economic and environmental costs, while accounting for the spatial distribution of the resources with respect to where they will be used. Liu et al. (2017) present a mathematical optimization model for water networks in industrial parks that includes direct water reuse and accounts for the predictable (development and adjustment) variations in the planning strategies for multi-period concern. Alnouri et al. (2018) addressed both brine treatment and water integration problems by investigating how ZLD options can optimally be incorporated onto water networks. Sujak et al. (2017) present a novel holistic approach that economically explores all water minimization options in the water management hierarchy for the design of cost optimal water networks; furthermore, the model is capable of allocating which resource (water or wastewater) should go to which end (elimination, reduction, reuse, regeneration, and outsourcing). However, because all network parameters have a degree of uncertainty associated with them, Poplewski (2015) introduced an optimization model that deals with these uncertainties by designing an optimum flexible water network that yields minimal fresh water consumption and a minimum number of pipelines but fulfills all constraints and uncertain parameters.

Other studies investigated the optimization of other parameters within a water treatment network, such as energy. Ibrić et al. (2014) presents the synthesis of heat integrated water and wastewater networks; the superstructure of the possible network includes heat exchanges, process water units, and wastewater treatment units. Similarly, Ahmetović et al. (2014) combines all three networks (heat exchanger network, water network, and wastewater treatment network) into a superstructure that combines water and heat integration; the applied optimization model seeks to minimize the total annual network cost. Ibric et al. (2017) studied the use a heat-integrated water network superstructure for the synthesis of both individual and interplant water networks, with the objective of minimizing network operating cost (including piping installation costs). González-Bravo et al. (2017) present an overall approach for the design of water and power distribution networks taking into account the size of the network, its location, in addition to other economic (maximizing profit), environmental (minimizing greenhouse gas emissions), and social (maximizing job creation) factors.

Meanwhile, this work proposes an optimization strategy that allows the identification and screening of practical and economic ZLD options for brine treatment, so as to facilitate the identification of cost-effective end-of-pipe ZLD systems that can accommodate stringent environmental considerations when imposed. Existing ZLD systems tend to center on evaporation and/or crystallization; however, with increasing flowrate and varying system characteristics, these technologies are not always solely the optimal selection (Tillberg, 2004). As such, ZLD cannot be achieved with a single technology, necessitating the use of a combination of technologies (Subramani and Jacangelo, 2014; Tillberg, 2004). Furthermore, obtaining reliable and efficient ZLD configurations mostly revolves around designing such systems in a way that would maximize water recovery, minimize energy consumption, while accounting for any recovered salts, as a side product. Furthermore, the brine wastewater generated by different industries varies in quantity and quality, thus necessitating custom system design (Tillberg, 2004). As such, the superstructure proposed in this work simplifies the process by providing a system template, where the user simply enters the system characteristics and specifies the ZLD technology pool available. The optimization model categorizes selected technologies and allows the user to generate an optimal ZLD scheme