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Feasibility study of an electrodialysis system for in-home water desalination in urban India

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A B S T R A C T

Poor quality of drinking water delivered to homes by state utilities, and a large reliance on brackish ground water resources in parts of urban India, has resulted in the adoption of in-home water treatment solutions. The only existing in-home water treatment solution capable of desalination is reverse osmosis (RO). However, existing RO products can recover only 25–50% of the feed water supplied as usable product water. In this study, an alternative solution that relies on electrodialysis (ED) was designed and experimentally shown to achieve a recovery of 80%, producing 12 L/h of water at the desired salinity of 350 ppm from a feed salinity of 3000 ppm. The cost and size of the proposed system were also found to be comparable to existing in-home RO systems. In-home ED water treatment systems could compete with existing RO products while providing the advantage of improved water-conservation in water-stressed India.

1. Introduction

The Indian government has expressed an aim to provide clean drinking water to all of its citizens (Government of India, 2002), but this target has yet to be achieved. While the percentage of people with improved access to drinking water sources has increased from 69–92% nationally from 1990 to 2010, an estimated 97 million people still rely on surface water, unprotected dug wells and springs, or water delivered by carts (WHO/UNICEF, 2012). Even among those with improved access, the 2011 census found that piped water is supplied to only 71% and 35% of urban and rural households, respectively (Census of India, 2011). Furthermore, no major city has developed the capability to provide a 24 h water supply, with most supplying only 4–5 h of water each day (Mckenzie and Ray, 2005). Quality of the available water in urban environments is also a concern since only 62% of the tap water supply is treated before delivery (Census of India, 2011). A survey conducted by the Society for Clean Environment (2003) found the proportion of tested water samples that were unfit for drinking to be as high as 70% in certain municipal wards of Mumbai (Sridhar, 2003).

Compounding the problem of poor access and quality is the salinity of available water. There is a high reliance on groundwater resources to meet the population needs across much of the country. According to a study performed by the Central Ground Water Board, 60% of this groundwater was classified as brackish (Board, 2010). Water from these sources was characterized as having high salt content with total dissolved solids (TDS) ranging from 500 ppm (ppm) to 3000 ppm. This salinity exceeds the 500 ppm TDS standard recommended by the Bureau of Indian Standards (BIS) for drinking water (Bureau of Indian Standards, 2012), and is indicative of poor palatability. The consumption of high salinity water may also pose adverse health effects including gastro-intestinal irritation (Bureau of Indian Standards, 2012) and the development of kidney stones (Bellizzi et al., 1999). It has been therefore hypothesized that water treatment methods that reduce levels of TDS, improving taste in the process, will experience high rates of adoption (Wright and Winter V, 2014).

Since the current public infrastructure is unable to reliably deliver safe, desalinated, and uncontaminated water to homes, consumers have turned to in-home water purification. However, methods which include straining water though a cloth, boiling, or ultraviolet (UV) treatment do not address the high levels of TDS present in the water. The only commercially available in-home water treatment method currently used in urban India that can remove TDS is reverse osmosis

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Nomenclature

Acronyms

AEM	Anion Exchange Membrane
BIS	Bureau of Indian Standards
CEM	Cation Exchange Membrane
CCRO	Closed Circuit Reverse Osmosis
ED	Electrodialysis
EDR	Electrodialysis Reversal
ID	Internal Diameter
INR	Indian Rupee
L	Liter
L/h	Liters per Hour
M	Molarity
PPM	Parts per Million
RO	Reverse Osmosis
RR	Recovery Ratio
TDS	Total Dissolved Solids

Symbols

A	Membrane area (m2)
B0	Falkenhagen equation constant
B1	Falkenhagen equation constant
B2	Falkenhagen equation constant
D	Diffusion coefficient (m2/s)
F	Faraday constant (C/mol)
i	Current density (A/m2)
I	Current (A)
l	Thickness of membranes (mm)
L	Gap between membranes (mm)
MW	Molecular weight (g/mol)
N	Number of cell pairs
p	Pressure (MPa)
P	Power (W)
V^t	Tank volume (L)
Q	Internal stack flow rate (L/h)
r	Resistance (Ω-cm2)
R	Gas constant (J/mol-K)
S	Salinity (ppm)
t	Time (s)
t+	Transport number of cation
t-	Transport number of anion
T	Temperature (K)
v	Flow velocity (cm/s)
Vol	Volume
z	Charge number

Subscripts

a	Anion exchange membrane
c	Cation exchange membrane
ch	Channel
con	Concentrate
dil	Diluate
f	Feed (input water)
p	Product (output water)

Greek

ϕ	Current efficiency
Π	Osmotic pressure

(RO). However, in-home RO systems operate at low water recoveries (25–50% (KENT RO Systems Ltd; Hindustan Unilever Ltd, 2014)), thereby further stressing the limited resources.

Conversations with Tata Chemicals Ltd (Shah, 2014)., a provider of in-home RO systems in India, informed us that there is an unmet need among consumers for an in-home desalination product that can recover more water than current in-home RO systems. To meet this need, we considered alternatives to RO such as electrodialysis (ED) (Strathmann, 2010), capacitive deionization (Oren, 2008), thermal desalination technologies and a higher recovery version of RO called closed circuit reverse osmosis (CCRO) (Efraty et al., 2011). Our evaluation informed us that ED was the technology alternative that was most ready for deployment in India. Key highlights of this evaluation are discussed in Appendix A.

ED is an alternative method for desalination that can provide higher recovery and lower energy consumption compared to RO for the groundwater salinity range present in India (Wright and Winter V., 2014). This technology has been widely implemented at a larger scale for applications that include waste-water treatment, production of potable water, and salt production (Strathmann, 2010). Pilat (2001, 2003) had reported the use of ED for in-home water treatment applications along with a summary of the features of a few systems that were commercially deployed in Russia. One system was for the desalinating 3000 ppm water to produce 50 L/h of drinking water at 300 ppm. However, the cost of the systems was not mentioned. Important technical information such as membrane area, water flow rate within the stack, and membrane specifications were also not reported which made estimating cost difficult. Since the publication of Pilat's work, significant advances in RO membranes have made in-home RO systems less expensive. With the reported information, it was not possible to effectively characterize the technical design and the economic feasibility of in-home ED in urban India, where the required flow rates are lower and systems needed to be more compact than the systems reported by Pilat (Pilat, 2001). Recent progress made in the process modeling of ED (Ortiz et al., 2005) also enable optimizing and characterizing in-home ED systems in a way that has not been possible before.

1.1. Objective

In combination with necessary additional pre and post-treatment, ED demonstrates the potential to satisfy an unmet consumer need: a cost-competitive, high recovery in-home desalination and water treatment system. In this work, we assess the design requirements for an in-home water desalination system for use in urban Indian households, and evaluate the technical design and economic feasibility of implementing the simplest configuration of ED to serve this application. The design requirements for an in-home desalination system are first presented. An ED system architecture appropriate for in-home desalination was selected. An analytical process model for ED was used to optimize an experimental ED stack design that could achieve the design requirements. Results from our technical feasibility tests highlighting an optimal ED stack design, a conceptualization of the complete in-home ED water treatment product and an estimate of the cost of the final product are presented. Limitations of our study and recommendations for future work are also discussed.

2. Design requirements

2.1. Requirements drawn from existing products

There are different types of water purifiers currently available in the