Desalination 356 (2015) 314–327

Contents lists available at ScienceDirect

Desalination

journal homepage: www.elsevier.com/locate/desal

Technology for freeze concentration in the desalination industry

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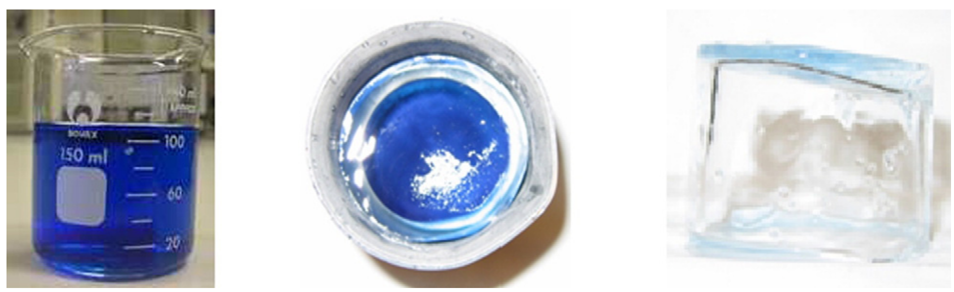
HIGHLIGHTS

- Review of processes for desalination by freeze concentration
- Developments in freeze concentration methodologies in food, wastewater and desalination industries
- RO-freeze desalination hybrid process

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 15 August 2014
Received in revised form 15 October 2014
Accepted 17 October 2014
Available online 10 November 2014

Keywords:
Desalination
Freeze
Direct
Indirect
Eutectic

ABSTRACT

The world is currently facing the prospect of a severe global shortage of fresh water alongside finite energy resources and the development of energy-efficient desalination methods is of paramount importance to solve these complex problems. In this paper the basic principles of freeze concentration processes are presented. Even though the process has the advantage of low energy usage and high concentration factors, only lab and pilot scale studies have been conducted in the desalination industry and application of the process has been limited due to the dominance of more traditional thermal and membrane technologies. Finally, the paper looks at the future applications for freeze concentration and discusses the possibility of application to high saline brine wastes in hybrid-technology.

Contents

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http://dx.doi.org/10.1016/j.desal.2014.10.023

1. Introduction

Water is a vital cornerstone of everything accomplished in modern society and the over-exploitation of existing fresh water supplies along with the increasing demand for water for drinking, agriculture and industry is going to be a major problem in the future. According to 'The Millennium Development Goals Report 2012' [1], 783 million people, or 11% of the global population, remain without access to an improved source of drinking water and almost 2.5 billion do not have access to adequate sanitation. The World Water Council estimate that the planet will be around 17% short of the fresh water supply needed to sustain the world population by 2020 [2]. Of all the water in the world, the majority of the Earth's water is contained in the oceans (~97%), while another 2% is trapped in icecaps and glaciers, resulting in less than 1% being accessible as fresh water [3–5]. Taking these figures into account, the oceans represent a virtually unlimited supply of water, however, seawater itself is unsuitable for human consumption and industrial/agricultural uses without treatment. For this reason, desalination has become an important method for the production of fresh water with the daily desalination capacity estimated as 71.9 million m^3/day at the end of 2011 [6].

Desalination for water supply has grown steadily since the 1960's. Patents filed in 2010 for desalination technologies are double that of 2005, demonstrating the increasing interest and research activity in this field [7]. Based on the process, desalination plants are usually characterized into two main types, thermal processes (including multi-stage flash (MSF), multi-effect distillation (MED), vapor compression distillation (VC), freezing) and membrane processes (reverse osmosis (RO), forward osmosis (FO), electrodialysis (ED)), although there are other processes such as ion exchange and hybrid processes which may also be used. Details and reviews of these technologies and methods are given elsewhere [3,4,8–10]. RO (often referred to as seawater reverse osmosis — SWRO) has become the most internationally widespread desalination technology [11]. In the period 2005–2008, the annual worldwide contracted capacity of RO increased from 20 to 35 million m^3/day [12] which represents over 50% of the total installed desalination capacity on the planet [13,14]. The world's largest desalination plant at Ras al-Khair in Saudi Arabia became operational in 2014 and has the capacity to produce 1.025 million m^3/day, through a hybrid system which implements both the multistage flashing (MSF) and reverse osmosis (RO) technologies [15].

Although desalination technology has progressed rapidly, the technology itself is still imperfect. Despite best efforts, desalination is costly and largely inefficient. The desalination process takes a huge amount of pressure or heat to separate the water from the salt and other impurities, which requires energy and therefore money. Large quantities of concentrated brine need to be disposed of [16], and the desalination process is also considered to be detrimental in terms of environmental impact and cost [17,18]. Therefore, selection of the process to be used and optimisation are vital for successful desalination operations.

In this paper the freeze-melting process will be considered for the purposes of desalination. The fact that the freeze-melting process can purify and concentrate liquids has been known for many years [19]. The simplest natural example is that sea-ice has a much lower salt content than sea-water, a phenomenon used by the inhabitants of the polar regions as a source of drinking water. From an industrial-separations viewpoint, the freeze-melting process has a number of important advantages [9,20]:

a) A very high separation factor,
b) High energy efficiency since the latent heat of freezing is low compared to the latent heat of evaporation (333.5 kJ/kg and 2256.7 kJ/kg, respectively [21]), which leads to a lower energy requirement in comparison to other processes,
c) Insensitive to biological fouling, scaling and corrosion problems because of the low operating temperature, which means less use of chemicals and thus lower operating costs.
d) Absence of chemical pre-treatment means no discharge of toxic chemicals to the environment.
e) Inexpensive materials of construction can be utilized at low temperature, which results in lower capital cost.

Despite these important advantages for freeze-melting processes (low energy and low temperature), this technique has only been used to a very limited extent industrially for desalination. This has been largely due to a very conservative approach to the adoption of new technology, the perception that such a process would be mechanically complex, the lack of appropriate test data and that water is a low value product. However, these caveats have recently become less important due to the pressing need for more effective solutions to water pollution problems and the development of mechanically simpler freezing technology. In the rest of this paper the main methods currently being investigated for freeze separation in desalination will be reviewed and the possible uses of this technology will be discussed.

2. History of freeze separation processes

Freeze separation is a technique first thought to be used by sailors in cold climates to get fresh water on board ships. Sailors found that, when seawater was frozen, all the impurities were concentrated into the center of the ice block. The majority of the ice block was made up of high purity frozen water [19]. Due to the freezing temperatures of the water, the ice layer was often found to be potable for human consumption. This discovery meant that sailors could simply thaw the outer ice and take drinkable water; hence, ships could travel for longer without the need to stop at a water source to replenish their supply.

The first experiments on freeze separation and concentration were carried out in the late 1600's before the invention of refrigerators or freezers to aid the process. Due to this, testing had to be carried out in cold conditions or winter times. The first instance of fresh water from sea ice was published by Danish Physician Thomas Bartholinus in 1661 [22], closely followed by others such as Boyle [23] and Kircher [24] who witnessed the fact that pure water ice held a pocket of liquid brine containing impurities within the high purity water ice block after being frozen at sea.