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Can a hybrid RO-Freeze process lead to sustainable water supplies?

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ABSTRACT

In this paper we investigate the potential for using suspension crystallisation for the production of clean drinking water from a seawater source. The experimental results show that the produced water from the suspension crystallisation plant not only meets water quality standards but is comparable in ionic composition to premier bottled water from around the globe. The experimental results obtained from a pilot scale suspension crystallisation unit showed that the achievable water recovery was around 41% and the salt rejection ratio reached over 99%, which is comparable with most desalination technologies. Moreover, a hybrid RO-Freeze plant has been proposed that is capable of significantly increasing the potable product water that could be achieved by RO alone (~400% increase), while simultaneously concentrating the RO brine (used as feed water) producing a super brine of ~13 wt%. While there is a cost to this additional process in terms of capital and energy that must be quantified, the obvious increase in water harvest and reduction in residual brine quantity lead to a very attractive desalination process. If the energy demands are acceptable, then this technology could lead to a more sustainable water future.

1. Introduction

Along with energy, shelter and food, access to a source of fresh clean drinking water is essential to all life on earth. Today, the over-exploitation of existing fresh water supplies along with the increasing demand of water for drinking, agriculture and industry is generating a critical availability issue and according to the United Nations [1], 783 million people, or 11% of the global population, remain without access to safe drinking water and almost 2.5 billion do not have access to adequate sanitation. The World Water Council estimates that the planet will be around 17% short of the fresh water supply needed to sustain the world population by 2020 [2]. The world's oceans contain around 97% of all water on earth and many view this reservoir as an unlimited water resource that should be exploited for future needs. Unfortunately, as most people are aware, seawater is contaminated with high levels of salt (~35,000 ppm) and other biological, physical and chemical agents and refining is necessary to form a clean water product that is safe for drinking. Based on the technology employed, desalination plants are usually characterised into two main types; thermal processes (including multi-stage flash (MSF), multi-effect distillation (MED) and vapour compression distillation (VC) and membrane filtration processes (reverse osmosis (RO), nanofiltration (NF), forward osmosis (FO), electrodialysis (ED)), although there are other technologies such as ion exchange and hybrid processes may also be used. Details and reviews of these technologies and methods are available elsewhere [3–8]. Currently, the annual worldwide contracted capacity of RO is 37 million m^3 per day which represents ~74% of the global total installed desalination capacity [9].

Although desalination technology has progressed rapidly, the technology itself is still imperfect. Despite best efforts desalination is costly and largely inefficient. The desalination process requires a huge amount of pressure or heat to separate the water from the salt and other impurities, which in turn requires energy and therefore money. Large quantities of concentrated brine are produced and need to be disposed of [10] and the desalination process is also considered to be detrimental in terms of environmental impact and cost [11,12]. Therefore, selection of the most appropriate process to be used and optimisation is vital for successful desalination operations.

In this paper a hybrid RO-Freeze technology process will be considered for the purposes of increased sustainability desalination. The fact that Freeze technology can purify and concentrate liquids has been known for many years. The simplest natural example is that sea-ice has a much lower salt content than seawater, a phenomenon used by the inhabitants of the Polar Regions as a source of drinking water. The basic

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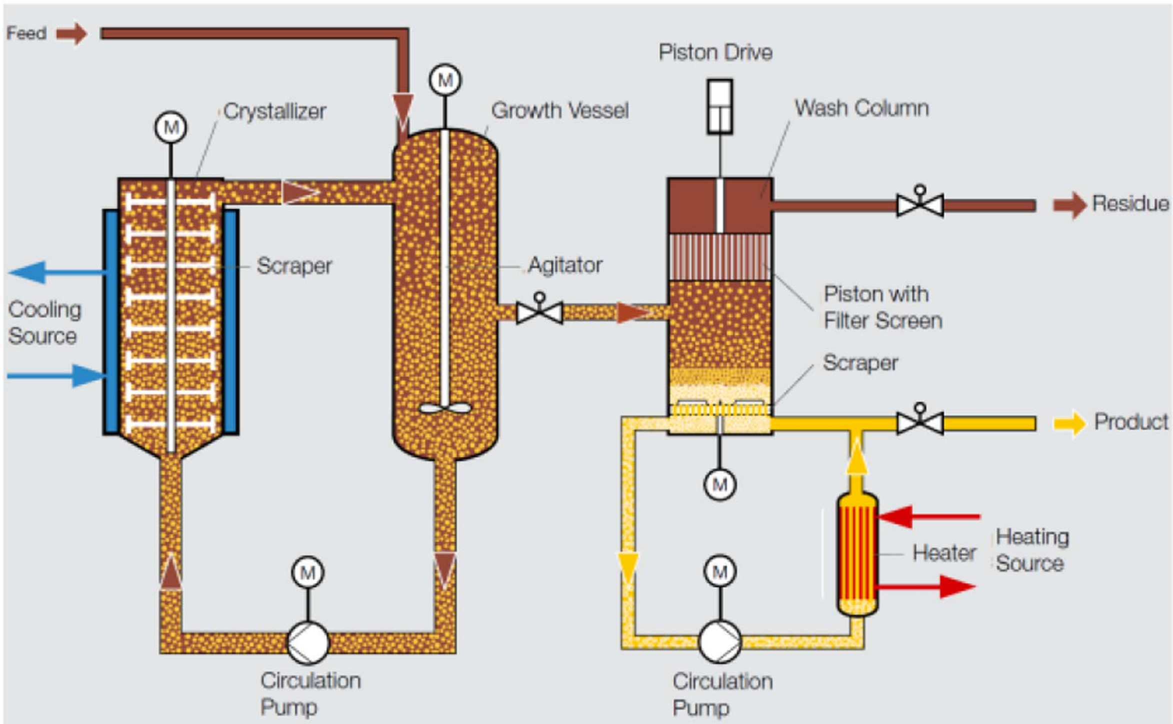

Fig. 1. A process flow diagram of a typical suspension crystallisation unit.
(Taken from [20])

Freeze process involves three simple stages:

1. The water sample (seawater) is partially frozen.
2. The ice crystals generated are separated from the remaining liquids.
3. The ice crystals are melted to yield clean water and the residue liquid (brine) is disposed.

The Freeze process and Freeze technologies have been extensively reviewed in two recent papers [13,14] and from an industrial separations viewpoint, Freeze technology has a number of important advantages:

- A very high separation factor,
- 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 [15]), which leads to a lower energy requirement in comparison to other processes,
- 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.
- Absence of chemical pre-treatment means no discharge of toxic chemicals to the environment.
- Inexpensive materials of construction can be utilised at low temperature, which results in lower capital cost.

Despite these important advantages for Freeze technology this technique has only been used to a very limited extent industrially for desalination and one of the major prohibiting factors is a lack of appropriate test data. In previous work we demonstrated the Freeze process for the recovery of clean water from synthetic saline solutions and Arabian Gulf seawater using a commercially available ice-maker at bench scale [16]. The work progressed to demonstrate a hybrid RO-Freeze process to improve desalination water recovery using a commercially available falling film unit at pilot scale [13]. In this work, we further demonstrate the capability of Freeze technology for desalination by considering the use of a suspension crystalliser in a hybrid RO-Freeze process. In contrast to the falling film unit used previously which generated both a low concentration and super concentrated brine, the suspension crystalliser has the capability to generate clean water from the discarded RO brine. Thus, potentially increasing the clean water recovery from the process.

2. Description of suspension crystallisation and basic operation

Suspension-based melt crystallisation is a highly selective, low energy consuming and solvent-free separation process used for the purification of organic chemicals [18,19]. This technology is capable of achieving high purity products and ecological production methods [18]. Suspension-based melt crystallisation has previously been used for purifying various chemicals and concentrating waste water. Some typical applications are; acetic acid, acetonitrile, adipic acid, benzene, caprolactam, durene, ethyl lactate, hexamethylendiamine (HMD), ionic liquids, lactic acid, methylene diphenyl isocyanate (MDI), methacrylic acid, *o*-phenylphenol, p-Diisopropylbenzene, p-Dichlorobenzene, p-Chlorotoluene, p-Nitrochlorobenzene, p-Xylene, phenol, trioxane, and waste water [18,20]. According to Ulrich and Glade [18], the important advantages of the suspension-based melt crystallisation approach are:

- superior purification can be produced from a single crystallisation stage,
- higher crystal production rate per unit volume of equipment,
- suspension crystallisation process uses less energy to attain the same separation as solid layer crystallisation,
- the suspension crystallisation process is often carried out in a continuous mode, whereas solid layer crystallisation is usually carried out in batch mode.

According to Sulzer [20], suspension crystallisation plants consist of two loops, i.e. crystallisation and separation loops, as shown in Fig. 1. The main equipment in the crystallisation loop included a crystalliser, a stirred growth vessel, and a circulation pump. The separation loop contains a piston type wash column, circulation pump, scraper, tube