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Investigation of freeze crystallization and ice pressing in a semi-batch process for the development of a novel single-step desalination plant

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ABSTRACT

Potable water production is an essential but energy intensive process and usually requires many chemicals. Furthermore, small-scale plants are not yet available because of the problems associated with downscaling the thermal evaporation or reverse osmosis processes. Freeze crystallization is an alternative, especially for the self-sufficiency of potable water in remote areas. The use of a crystallizer and a separate press in combination with a perforated pressing mold has shown that the desalination of saltwater can be achieved by pressing the ice only; no additional washing step is necessary. A pressing force of 37.4 kN (100 bar) and a holding time of 180 s were found to be sufficient. Therefore, these parameters were used to design a single-step plant, which also showed good results in the case of ion expulsion. Nonetheless, the variation in the test parameters showed their influence on crystal growth and crystal purity and demonstrated the need to find the optimal design parameters for future continuously operating systems.

1. Introduction

In relation to the water supply, water purification is one of the most significant challenges that must be solved in the near future. In particular, changes to the water balance caused by ongoing climate change will further aggravate supply problems [1,2]. This fact will even further exacerbate by an increasing world population [3,4]. In areas such as Southeast Europe, the Middle East, and the West Coast of North America, which have suitable conditions such as significant wealth, desalination by reverse osmosis can help to close the supply gap. Conversely, areas with a vulnerable water supply like North Africa, Southwest Asia, and the Southwest Coast of South America can only use evaporation technology if oil or other cheap energy sources are available. With interest moving toward zero-carbon technologies, some desalination processes will be hard to retain in the future [5,6].

Thus, there is an urgent need to develop new desalination plants to satisfy the requirements of households in remote areas or with limited access to energy sources. The essential factors for realization depend on the desalination technology and the workability as well as on the affordability and environmental friendliness. Existing technologies, like reverse osmosis and thermal evaporation, have the disadvantage of requiring a range of chemicals, which make them unsuitable for sustainable processes [7]. Furthermore, they are hard to power with renewable energy sources, which makes the whole processes expensive and complex [8,9].

However, freeze desalination can be one method to overcome this problem [10]. It has several advantages as low energy consumption and the possibility of combining it with renewable energy sources. Furthermore, this technology can, in turn, be connected to heat pumps, offering a high efficiency through small temperature gradients caused by heat integration, thereby reducing investment costs [11]. Experiments show that water can be desalinated independently from the dissolved impurity avoiding additional chemicals during the process [12]. Therefore, this process with the chance of customizable scaling seems to be ideal for the use in remote areas, making them interesting for small communities, villages and hotel complexes [7,13,14].

Freeze crystallization in contrast to other technologies is based on the effect that all dissolved molecules are expulsed from the growing ice crystal and then concentrated within the surrounding liquid [15]. During this process, the melting temperature decreases due to an increasing salt concentration [16]. Furthermore, during crystal growth, some liquid volumes can be entrapped within the crystal. This effect is heavily influenced by the concentration gradient whilst ions are expelled but not already diluted. This concentration gradient can be prevented by high liquid turbulences around the ice crystal or a slow growth rate [17]. Therefore, operating conditions are an important influence on the purity of the product.

Already investigated methods describe different plants and methods

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Nomenclature

Symbols

A	area [m^2]
C	constant [−]
c	concentration [wt%]
d	diameter [m]
F	pressing force [N]
Fr	Froude number [−]
g	gravity [m/s^2]
h	heat transition coefficient [W/(m^2 K)]
l	length [m]
m	mass [kg]
$\dot{m}$	mass flow rate [kg/s]
n	rotational speed [1/s]
Nu	Nusselt number [−]
Pr	Prandtl number [−]
q	volumetric flow rate [m^3/s]
R	removal efficiency [%]
Re	Reynolds number [−]
t	time [s]
u	velocity [m/s]
w	mass fraction [%]

Greek

α	heat transfer coefficient [W/(m^2 K)]
γ	coefficient
ε	coefficient
η	dynamic viscosity [Pa s]
ϑ	temperature [°C]
λ	heat conductivity [W/(m K)]
ρ	density [kg/m^3]
φ	volume fraction [%]

Subscripts

a	axial
$B\&A$	Bott and Azoory
$B\&L$	Bel and Lallemand
e	equivalent
el	electrical
f	fluid
fl	flow
i	inner
l	liquid
m	mixture
o	outer
r	rotor shaft
S	stirred
s	solid
St	stein
Sc	screw/scraper
t	tangential
W	vessel wall
Z	Zlokarnik

to crystallize and separate the ice from seawater [18–22]. However, it was not possible to produce potable water by freezing the water only. A post-treatment step has to be installed downstream to ensure that no brine is attached to or trapped within the crystal anymore. The usually used process is thereby washing with the melted product [15]. This, of course, leads to a reduction of product and thus to higher costs. Kiesskalt reported that pressing and centrifuging could also be used as post-treatment steps, but recommended centrifuging only [23]. One firstly described scratcher to avoid adhering ice on the cooled surface was suggested by Cao, who, unfortunately, did not describe any experiments nor if he used any kind of post-treatment [24].

This study is based on previous investigations on seawater desalination processes and several post-treatments [10]. Thus, it reports freezing crystallization in combination with pressing as a batch process using a continuous screw crystallizer and a pressing mold with a 50 t press. Furthermore, based on these results a new process is developed that combines freezing and pressing in a continuously operating potable water producing test plant.

2. Materials and methods

2.1. Reagents

Samples were prepared prior to experiments using deionized water and sodium chloride purchased from Sigma–Aldrich. An initial liquid volume of 30 l was prepared and used until consumed. A real seawater test sample was taken from the Atlantic Ocean next to La Rochelle, France. The crystallizer was always flushed with test solution prior to experiments.

2.2. Sample analysis

To determine the salt concentration in the water, brine, or melted ice, a Greisinger GMH 5450 conductivity meter was used, and, for the sample from the Atlantic Ocean, inductively coupled plasma mass spectrometry (ICP-MS) and ion chromatograph (IC) from the TU Berlin were used.

Crystal structure analysis was performed using a self-made cooling chamber (Fig. 1), for which the temperature was adjusted to be consistent with the cooling temperature of the crystallizer, ensuring a stable crystal shape. Light-emitting diodes (LEDs) were installed at the

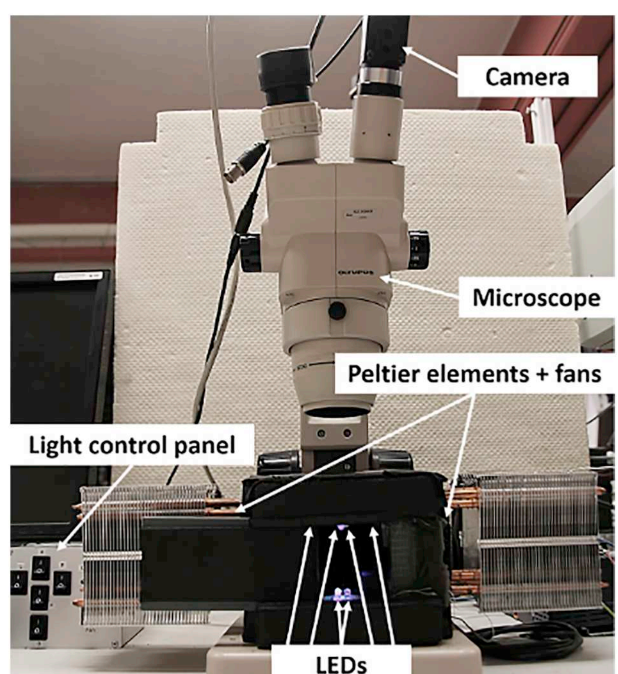

Fig. 1. Microscope with a camera and cooling chamber.