Energy Conversion and Management 168 (2018) 407–420

Contents lists available at ScienceDirect

Energy Conversion and Management

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

Numerical investigation of indirect freeze desalination using an ice maker machine

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ARTICLE INFO

Keywords:
CFD
Freezing
Desalination
Salinity
Salt separation
Temperature

ABSTRACT

To overcome the water shortage problem, sea water desalination is a prospective answer in order to cater for the escalating demand for fresh water. Freeze desalination is where the freezing of sea water permits the separation of salts from the water in order to produce potable water. The ice formed is of pure water as the ice crystal lattice prevents the inclusion of any salts. The lower energy usage of freeze desalination in comparison to other desalination processes is the key advantage; as the latent heat of fusion (333.5 kJ/kg) is about 1/7th that of the latent heat of vaporisation (2256.7 kJ/kg). CFD ANSYS fluent software has been used to simulate the freeze desalination process; results were compared with experimental tests showing a maximum deviation of 0.93% for the temperature change during the ice forming process and the percentage errors obtained for the salinities of ice and brine were 15% and 10.5% respectively. From parametric analysis study, results showed that, as the freezing temperature reduces, the volume of the generated ice block increases, where at 225 K freeze temperature, 5 times more ice was produced compared to that at 257.15 K, but with a high salinity level of 3.02%. Results also showed that the lowest average salinity achieved was 0.5% at an ice layer thickness of around 4 mm using a freezing temperature of 245 K. This is higher than the 0.1% salinity level recommended by the World Health Organization (WHO) standards as safe to drink water. Therefore, a second stage freezing process was applied to this 0.5% saline water to produce the required salinity level. Results showed that the achieved average ice salinity in the second stage of freezing process was below 0.05% which is regarded as good quality drinking water; also freezing at 225 K temperature produced the largest pure ice volume. These results highlight the potential of using freeze desalination to produce drinking water.

1. Introduction

For the growth of any human society, a vital element is water for all inhabitants in this planet [1,2]. The estimated value of the source of freshwater on Earth is about 3%, signifying the shortage of water. The rise in population, changes to socioeconomic conditions, increase in requirement of water for agricultural/industrial consumption, etc. causes an excess growth in water usage thus swelling water scarcity worries [3–7].

The effect of growth in processes for improving water quality due to the development of technology has been seen over the past years [8]. Freshwater being made by the removal of dissolved minerals from sea water is desalination; as it verifies to be an answer to the water shortage issue [9]. During the years 2008 to 2013, a rise in the capacity to generate desalinated water has risen to 57% annually. In the year 2013, 300 million people were served as 1700 plants were used to produce 80 million m^3/day [9,10]. The water shortage issues are significantly condensed and the quality of water is enhanced thus in turn bettering the quality of life and economic status by desalination technologies [11]. The two main practises used for desalination are thermal and membrane methods [12–14]. Membrane methods incorporate the reverse osmosis (RO) technology where membrane fouling is severely seen. Thermal methods make use of multi-stage flash desalination (MSF) and multiple-effect distillation (MED), though one of the main challenges in these methods is high energy consumption [15–17]. For small-scale applications, Vapour compression technology (VCD) is used [8]. The disadvantages of these desalination methods are high energy consumption and high operating costs [18], [19]. Correspondingly, due to the rise in many desalination plants in the recent past, the conventional desalination plants using fossil fuels would considerably increase the air pollution [20].

When compared to other desalination techniques, a great importance is given for freeze desalination (FD) due to its many advantages [21–26]. Given that solutes are prevented from being included due to the formation of ice, the salts are rejected in freeze desalination. The ice formed is of pure water where the crystal lattice prevents the

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https://doi.org/10.1016/j.enconman.2018.05.010
Received 3 March 2018; Received in revised form 2 May 2018; Accepted 4 May 2018
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Nomenclature

Symbols

A_{mush}	mushy zone constant (–)
$D_{i,m}$	mass diffusion coefficient for species (m^2/s)
$\overrightarrow{F_s}$	solutal buoyancy body forces (N)
$\overrightarrow{g}$	gravity (m/s^2)
H	enthalpy [energy/mass (J/kg), energy/mole (J/mol)]
$\overrightarrow{J_i}$	diffusion flux of the species (kg/m^2-s)
k	mass transfer coefficient (–)
K_i	partition coefficient of the solute (–)
m_i	slope of the liquidus surface (K)
N_s	number of species (–)
p	pressure (Pa)
T	temperature (K)
$\overrightarrow{v}$	velocity (m/s)
$y_{l,i}$	mass fraction of the liquid phase (–)
Y_i	mass fraction of the solute (–)

Greek symbols

β	liquid volume fraction (–)
$\beta_{s,i}$	solutal expansion coefficient (K^{-1})
ε	mall number (0.001) (–)
μ	viscosity of the fluid (Pa s)
ρ	ρ, is the density of fluid (kg/m^3)

Acronyms

CFD	computational fluid dynamics
FD	freeze desalination
LNG	liquefied natural gas
MED	multiple-effect distillation
MSF	multi-stage flash
RO	reverse osmosis
VCD	vapour compression desalination

Subscripts/superscripts

Eut	eutectic
i	solute
liq	liquid
liquidus	liquid
melt	melting
ref	reference
s	species
sol	solid
solidus	solid
*	interface

inclusion of any salts due to the nature of the ice crystal structure which is referred to as the water solidification phenomena [21,22]. Low energy usage by the freeze desalination process is indicated as the latent heat of vaporization is 2256.7 kJ/kg and the latent heat of fusion is 335 kJ/[23,24]. A variety of construction approaches and a range of materials are suitable in freeze desalination because of its low operating temperatures when compared to other distillation techniques that allows corrosion and scale formation [24]. Industrial water/waste water, brackish water with high salt content, etc. are substances that membrane processes usually cannot desalt but it is possible with freeze desalination. Freeze desalination allows the feed water to be of various types of substances and allows water properties with different concentrations for desalination [25]. Regasification of liquefied natural gas (LNG) can also be used for freeze desalination by consuming the cold energy from it [26]. In the freeze desalination process, this high quality energy can be utilized to freeze the feed saline water as most of the cold energy during the regasification of LNG is put to waste [15]. Globally, the desalination capacity is increasing and due to the on-going energy supply-demand discrepancy, these technologies can help to deliver answers to expand the economics of the renewable energy powered desalination techniques [27]. An adsorption system can also be used to conduct freeze desalination as Dakkama et al. [28] investigated a novel vacuum-direct freezing technique using an adsorption system for freeze desalination by using refrigerants.

Detailed parametric analysis has been carried out by Youssef et al. [29], which compared the performance of various desalination technologies, and ultimately showed that freeze desalination releases CO_2 emissions of about 5.5 kg/m^3. It also demonstrated that water production costs were only 0.34 $\$/m^3$; comparatively lower relative to other desalination technologies. In spite of decent separation efficiency, low

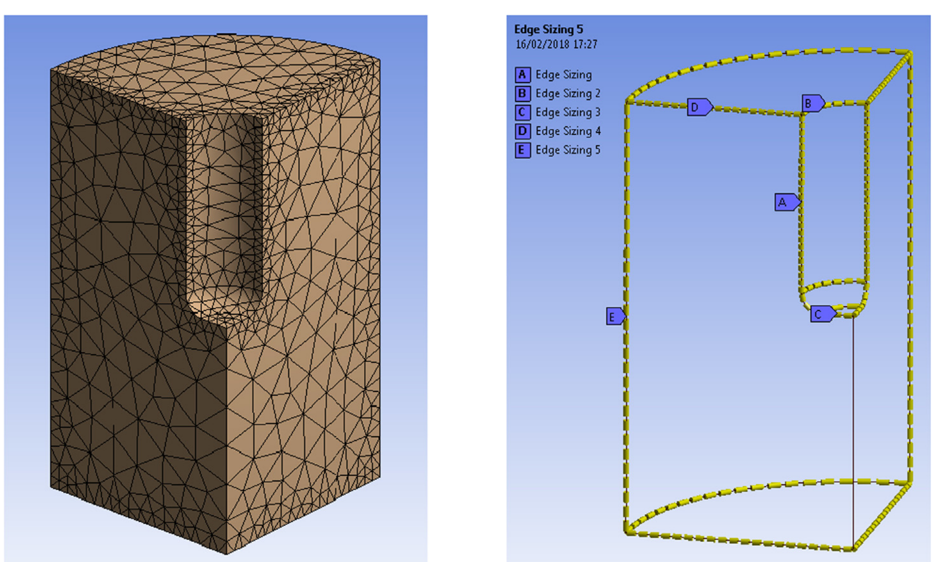

Fig. 1. Tetrahedral mesh (a) and edge sizing used (b).

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