Applied Energy xxx (2016) xxx–xxx

Contents lists available at ScienceDirect

Applied Energy

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

Zero thermal input membrane distillation, a zero-waste and sustainable solution for freshwater shortage

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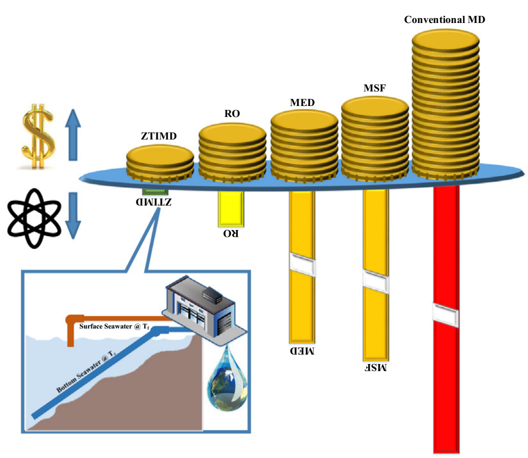
HIGHLIGHTS

- Zero Thermal Input Membrane Distillation (ZTIMD) feasible for seawater desalination.
- Freshwater produced at \$0.28/m^3 with energy consumption at 0.45 kW h/m^3 and waste-free.
- ZTIMD truly sustainable and could revolutionize seawater desalination industry.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 25 August 2016
Received in revised form 14 October 2016
Accepted 16 October 2016
Available online xxxx

Keywords:
Membrane distillation
Zero thermal energy input
Waste-free
Desalination
Feasibility

ABSTRACT

The innovative concept of a zero-waste, energy efficient, and therefore sustainable desalination strategy, Zero Thermal Input Membrane Distillation (ZTIMD), is demonstrated to be economically more effective than existing seawater desalination technologies by simulation based on a single-pass Direct Contact Membrane Distillation process using surface seawater as the feed and bottom seawater as the coolant. Thermal energy required for water distillation in the process was satisfied by extracting the enthalpy of the surface seawater using the bottom seawater as the heat sink. Under one of the favorable conditions, the proposed ZTIMD process could produce pure water with a cost of \$0.28/m^3 at a specific energy consumption of 0.45 kW h/m^3, which is significantly lower than that of the major existing seawater desalination processes, including the currently dominating technology, Reverse Osmosis (\$0.45–2.00/m^3). Some major advantages promised by the ZTIMD include (1) With no requirement of external thermal energy input, ZTIMD is an inherently energy-saving process, (2) it is economically competitive to existing desalination technologies, and (3) it is waste-free.

1. Introduction

Water scarcity due to population, agricultural, industrial growth and urbanization, which is further intensified by global warming and widespread droughts, has become a serious threat all over the world. Currently, one third of the global population is in short of clean water, and it is anticipated that over 1.8 billion people would experience absolute water shortage and two third of the population would be under water stress by 2025 worldwide [1,2]. Almost 70% of the earth surface is covered by water [3],

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http://dx.doi.org/10.1016/j.apenergy.2016.10.142
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Nomenclature

Symbol

Symbol	
a	amortization factor
C_p	specific heat capacity
d	diameter
dt	temperature rise
e	electricity cost
f	plant availability
h	heat exchanger cost per area
l	purchased piping cost per length
m	mass flowrate
m^*	membrane cost per area
P^*	vapor pressure
P_s	brake power
q	volume flowrate
r	replacement rate
RR	recovery ratio
T	temperature
U	global heat transfer coefficient
W	plant capacity
x	salt concentration
ΔH_v	heat of vaporization
ΔP_f	frictional pressure loss
η	efficiency
μ	viscosity
ρ	density

Subscript

Subscript	
c	coolant
f	feed
in	inlet
LMTD	logarithmic mean of temperature difference
m	membrane interface
min	minimum
out	outlet
p	permeate

however, only 2.5% of that water is deemed to be usable as freshwater [4]. Recovering freshwater from undrinkable water bodies such as oceans and brackish waters by means of desalination has become increasingly important over the past few decades [5–16]. For instance, Singapore is planning to increase the share of desalination in their water supply market from 10% at present to 30% by 2061. China is expected to roughly quadruple their current desalination capacity by 2020. In California, the largest desalination plant in the western hemisphere will produce 50 million gallons of drinkable water every day from pacific seawater with an investment of $1 billion by 2016 [1]. According to a recent analysis by Frost & Sullivan, the global desalination capacity is predicted to double by 2020 [17].

At present, desalination itself is not sustainable due to its consumption of extremely large quantities of energy, mainly fossil fuels [16,18]. As an example, Saudi Arabia with the largest desalination market in the world at a share of 17% [1], consumes 1.5 million barrels of oil every day to generate a daily desalinated water of 3.3 million m^3 [19]. This oil-for-water strategy is making freshwater the new oil in reference to its unsustainability [1]. It is of interest to mention that late Richard Smalley, a Nobel laureate of 1996 in chemistry, listed "energy" and "water" as the first and second among the top 10 problems facing the humanity for the next 50 years [19]. It has been argued that the use of renewable energy such as solar [20–23], geothermal [24,25], wind [26,27], and tidal [28,29] for desalination would result in longer-term sustainable water supply. However, such a desalination process is not economically affordable at large scale up to now despite of the extensive efforts worldwide [20,30,31].

The global desalination market is currently dominated by Reverse Osmosis (RO) [3,9,32–38] since it demands much less specific energy than thermal desalination processes [39–42]. Nevertheless, the 3–4 kW h/m^3 [19,43–46] specific energy consumption of RO still accounts for about 40% of the overall cost of the final product, which shows the process to be still quite energy intensive [43]. Furthermore, exergy analysis shows that remarkable irreversibility takes place in RO processes [47–50] and the aforementioned typical energy consumption in RO is approximately 600% more than the thermodynamic minimum energy required to reduce the salt concentration of seawater from 35,000 mg/L to that of drinkable water, i.e., 300 mg/L, at a water recovery of 40% [51]. In practice, commercial RO processes usually work at a water recovery in the range of 40–60%, which would generate even larger irreversibility. Other challenges in association with RO include its high operational pressure, sensitivity to the quality of raw feed, need for extensive feed pre-treatment, and the fouling and scaling problems [9,34,52–54].

Membrane Distillation (MD) is considered as the most promising emerging technology which has the potential to compete with RO in the desalination market [9,33]. MD has important advantages that set it apart from other desalination technologies. These include (1) nearly complete salt rejection even at high salt concentration of feed where RO normally fails, (2) possibility of using low grade heat, (3) ability of working at high water recoveries, (4) low tendency to fouling and scaling which would result in lower operation and maintenance costs and environmental impacts, and (5) chemical pre-treatment of the feed might be eliminated due to the mild operating conditions [9,33,55–60]. In addition, exergy analysis indicates that MD would be more appropriate if waste heat is available [50].

Nevertheless, MD has not yet been industrialized as a standalone desalination process at large scale and related studies have mostly focused on integrating MD as part of a hybrid process such as RO/MD and nanofiltration (NF)/RO/MD, where MD is utilized to achieve high overall water recovery that is not realistic with RO or NF/RO [61,62]. One of the main constraints of conventional MD desalination is its requirement of large quantities of thermal energy input to pre-heat the feed [62], which might be in the range of 600–9080 kW h/m^3 [21].

Extensive efforts have been made to reduce the costs or increase the sustainability of energy for MD desalination, and different approaches have been proposed including (1) use of low grade heat such as waste heat from industrial facilities [63,64], (2) use of renewable energy such as solar energy [22,30] and geothermal energy [25], and (3) introducing new configurations designed to partially recover the thermal energy [62,65,66].

Only a few techno-economic studies on MD desalination process are available in the literature, which provide valuable information on the key contributors to costs and the overall competence of the technology [21,22,25,57,67,68]. Al-Obaidani et al. [57] reported pure water costs of \$1.17/m^3 and \$1.25/m^3 for a Direct Contact Membrane Distillation (DCMD) process with and without heat recovery, respectively. For the DCMD plant without heat recovery, the authors showed that almost 61% of the operation and maintenance costs are spent to generate steam for heating purpose. Therefore, one could considerably reduce the