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A novel process for low grade heat driven desalination

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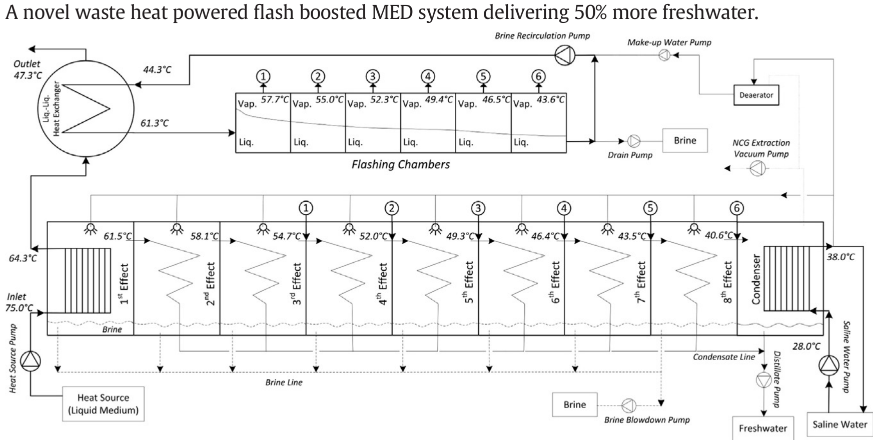
HIGHLIGHTS

- A flash-boosted multi-effect distillation process has been developed.
- The process maximally exploits the potential of waste sensible heat source.
- 40–50% more freshwater compared with conventional multi-effect distillation process.
- Auxiliary power consumption only increases modestly by 22–34%.
- 4% to 6% decrease in the specific capital cost

GRAPHICAL ABSTRACT

A novel waste heat powered flash boosted MED system delivering 50% more freshwater.



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ABSTRACT

Low grade process heat and geothermal energy with temperatures typically below 100 °C are significant untapped environmentally friendly resources for desalination. This article reports on a novel multi-effect distillation (MED) desalination process that is boosted by a multi-stage flashing process. Specifically the low grade heat first heats up the multi-effect distillation plant and is then maximally exploited through a multi-stage flashing process, with the produced steam of which being judiciously introduced into the multi-effect distillation plant for enhanced freshwater production. Compared with optimized conventional MED processes, the performance improvement is up to around 50% better in terms of freshwater production, with a modest increase in the pumping power consumption and 4% to 6% decrease in the specific capital cost.

Nomenclature

A	area (m^2)
a, α	constant
β	constant
BPE	boiling point elevation (°C)
C_P	specific heat capacity (kJ/kg.°C)
D_t	total plant production rate (m^3/day)
D_{FC}	generated vapor mass flow of the flashing chamber section (m^3/day)
Δh_{ref}	specific reference enthalpy of the distillate (kJ/kg)
$\Delta h_{avail.}$	maximum exploitable energy of the heat source (kJ/kg)
Δh_{ref}	specific reference enthalpy of the distillate (kJ/kg)
$\Delta \dot{H}$	rate of energy (enthalpy) transfer (MW)

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ΔP	pressure difference (kPa)
ΔT_{lm}	log mean temperature difference (°C)
ΔT_{st}	stage temperature decrement (°C)
h_f	enthalpy of saturated water (kJ/kg)
h_{fg}	latent heat (kJ/kg)
h_g	enthalpy of saturated steam (kJ/kg)
H	brine level (m)
HEX	heat exchanger
L	flash chamber length (m)
$Liq.$	liquid
$\dot{M}_{total}$	total freshwater mass flow rate (kg/s)
$\dot{m}$	mass flow rate (kg/s)
NCG	non-condensable gas
NEA	non-equilibrium allowance for flashing stage (°C)
NEA_{10}	non-equilibrium allowance for a 10-ft flashing stage (°C)
PR	performance ratio
T	temperature (°C)
$\dot{Q}$	heat transfer rate (kW)
U	overall heat transfer coefficient (kW/m^2.°C)
$\dot{V}$	volumetric flow rate (m^3/s)
W	brine flow rate per unit length of chamber width (kg/(m.s))
X	salinity
η	efficiency
Ψ	cost function for MED plants
Φ	cost function for MSF plants

1. Introduction

Nearly 71% of the surface of the earth (510×10^6 km^2) is covered by the oceans and the remaining 29% is occupied by the lands [1]. There is certainly bountiful water available on earth, but only 3% of which is drinkable and 97% is saltwater [2]. The demand for freshwater is set to increase significantly due to a combination of population growth, acceleration of industrialization in developing countries and increased agriculture activity throughout the world [3]. Water scarcity is the mismatch of the demand and availability of freshwater in a particular location. As mentioned above, traditional sources of available freshwater such as underground aquifers and surface water constitute a limited quantity worldwide. Furthermore, depletion and degradation of these sources are increasing at accelerating rates [4]. As a result, seawater desalination has become an essential option to augment freshwater resources, especially in developing countries and many arid zones. In 2011, approximately 150 countries worldwide used around 15,988 desalination plants (these include online, under construction and contracted) to produce desalinated waters [5]. The total global capacity of all online plants was 70.8 Mm^3/day [6] in 2011, which had a 10% increase in comparison with that in 2010. Based on the recent information from the International Desalination Association [6], 632 new plants have been added from mid-2011 to Aug-2012, which has increased the installed capacity to 74.8 Mm^3/day. These data indicate the potential of desalination market.

In general all applicable desalination processes can be divided into two main categories based on the phase change of saline feedwater.

- Desalination with phase change: This category includes all heat driven processes where freshwater is produced by evaporation and condensation phenomena. The principle examples are MED (Multi-Effect Distillation), MSF (Multi-Stage Flash), TVC (Thermal Vapor Compression), HD (Humidification-Dehumidification) and MD (Membrane Distillation). In Aug-2012, the share of MED and MSF technologies of the total installed capacity for all feedwater types was around 31% [6].
- Desalination without phase change: In this category, separation is achieved by passing saline water through membranes without involving phase change and RO (Reverse Osmosis) is the iconic example. RO's share of installed capacities was 63% in 2012 [6].

Desalination is an energy intensive process. For example the RO process has a high overall efficiency at the expense of consuming a large amount of electricity and for thermal processes such as MSF and MED they relate to large thermal energy consumption. Therefore in respect of production rate, economic feasibility and environmental friendliness, the optimization of desalination methods should be considered in the context of minimizing energy consumption. In the face of pressing concerns regarding anthropogenic carbon emissions and global warming, meeting an increasing worldwide demand for freshwater is not a simple matter of increasing desalination capacity. Sustainable and renewable/waste energy based approaches must also be considered.

Waste thermal energy has always been an important issue in the process industries. Management of waste heat resources is one of the important subjects in process plants. For this purpose waste heat streams is being divided into two major categories: high and low grades. High grade refers to those heat sources that are typically recovered by the plant processes, while low grade refers to those which are not economically viable to recover and rejected to the environment [7]. One option to utilize the low grade heat sources of a process plant is to produce freshwater for internal or external usage (e.g. [7–13]). Furthermore, low grade renewable energy resources such as geothermal with a wellhead temperature lower than 100 °C [14] can be considered for the desalination purposes (e.g. [14–22]).

One of the main advantages of low-grade heat sources is related to carbon dioxide emission and global warming issue. If the required energy hails from fossil fuel source then the freshwater production will contribute to carbon dioxide emission and consequently global warming. Low grade heat sources such as waste heat from process plants and geothermal energy generate minimal greenhouse gasses. This article introduces a novel MED process that is coupled with low grade sensible (<100 °C) heat sources.

2. Low grade heat driven multi effect distillation

In the temperature range of low grade sensible heat sources, MED is ideal as its top brine temperature varies between 60 °C to 75 °C. Fig. 1 shows a conventional MED system. In this system the feedwater is distributed onto the heat exchanger surfaces of the first effect. The heat source fluid that flows through the heat exchanger releases its energy to the distributed feedwater and evaporates a portion of the feedwater. The produced vapor then condenses in the heat exchanger of the second effect to evaporate more feedwater in that effect. The brine from the first effect is then purged. At the second effect, the evaporated feedwater goes on to power the third effect with the resulting brine being drained from the bottom of that effect. This process continues to the last effect (the fifth effect in Fig. 1) with the corresponding produced vapor entering the condenser section and condensed by the incoming saline water acting as a coolant. Part of the preheated saline water is then sent to the various effects as feedwater. In the context of geothermal and sensible waste heat sources, this process is inefficient as the outgoing heat source temperature is still sufficiently high [13].

Recently a novel boosted MED system tailored for waste heat streams has been reported [11,12,23,24]. In this method and as shown in Fig. 2, a steam booster unit is installed to better exploit the waste heat stream so as to increase the freshwater yield. This booster unit (or an evaporator) is powered by the outgoing waste heat source of the primary MED plant. The generated vapor from the booster unit is then introduced into an appropriate effect of the primary MED plant. This scheme substantially heightens the production rate, but the extent of improvement is limited by the temperature drop across the booster unit.

3. Description of the novel system — flash boosted MED (FB-MED)

To further exploit waste heat, an improved system has been developed, as shown in Fig. 3 [25]. The improvement is derived from the ability of the system to extract the maximal energy from the waste heat and