Desalination and Water Treatment
www.deswater.com

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doi: 10/5004/dwt.2012.2271

37 (2012) 69–76
January

Taylor & Francis
Taylor & Francis Group

Geothermal waters heat integration for the desalination of sea water

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Received 11 October 2010; Accepted 27 June 2011

ABSTRACT

The main objective of this work is to utilize the existing geothermal potential of the Greek island of Nisyros located in the southeastern part of the Aegean Sea for desalination of seawater. The technology most applicable for the exploitation of geothermal purposes is the multiple effect distillation process (MED). The exploitation of the geothermal hot water sources located in the island combined with an effective desalination technology can eliminate energy consumption from hydrocarbons, minimize the environmental impact and reduce dramatically the cost of fresh water. The determination of the overall environmental impact of the desalination plan by means of a Life Cycle Analysis, and the evaluation of the measure's economical feasibility by means of Cost-Benefit Analysis and Life Cycle Cost methods will be shown. Exergy Analysis of the process will determine its thermodynamic efficiency. This work is to determine and demonstrate the feasibility of a geothermal-driven power-desalination plant to provide high quality of water in sufficient quantity at affordable costs, while protecting the fragile island environment.

Keywords: Water desalination; Renewable energy; Geothermal energy; Potable water

1. Introduction

The energy demand issue in islands that are geographically distributed and incapable of central management has a specific nature due to small capacity energy production schemes that are most applicable. The fragile environment of the islands requires the application of energy production technologies and resource management schemes, which are ecologically rational. Their schemes must be adjusted to the specified areas concerned with their specific resources. Their environmental impact must be minimised. The fact that today islands are relying solely on imported energy fuels, further development must be achieved in the context of technological flexibility. Furthermore, it is obvious that advances must be made in the direction of renewable energy sources in order to equalise the energy balance of theses isolated regions.

The Mediterranean areas are among the regions of the world where fresh/potable water sources are very limited and the demand for potable water is expected to increase in the coming years. The demand for water is increasing due to several factors. There is a continuous development of the tourist industry, a demographic grown and increased per capita consumption, extension of the water distribution networks, increased irrigation and industrial development. Tunisia, Algeria, the scattering islands of the Mediterranean Sea or isolated areas around Mediterranean and the Middle East countries has a great potential of brackish water, which does not fulfils the WHO standards (Table 1). Seawater or brackish water desalination appears as a promising technique for potable water production.

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Table 1
WHO standards for potable water

Constitutes	Concentration (ppm)	
	Limited values	Max allowed values
TDS	500	1500
Cl	200	600
SO_4^{2+}	200	400
Ca^{2+}	75	100
Mg^{2+}	30	150
F^-	0.7	1.7
NO^{3-}	<50	100
Cu^{2+}	0.05	1.5
Fe^{3+}	0.10	1.5
NaCl	250	–
PH	7–8	6.5–9

Over the past decade, the number of desalination plants and their total capacity has almost doubled. Currently, the production capacity exceeds 32 × 10^6 m^3/d, and the number of plants has increased to more than 15,000 units. Examples of large and rapid growth are found in many countries. During the period 1996–2002, the desalination capacity in Spain has doubled. As a result, Spain became the leading producer in Europe, with more than 30% share of the installed desalination capacity in the continent. Currently, the desalination capacity in Spain is approaching 1.5 × 10^6 m^3/d. Another example is found in Saudi Arabia, where the production capacity stands at 5 × 10^6 m^3/d and is expected to double its capacity by the year 2020. Similar scenarios are also found in other countries, Oman, Kuwait and the United Arab Emirates, [1].

The disadvantage of the desalination is the high capital cost. Traditional desalination techniques such as reverse osmosis (RO), electrodialysis (ED) and multistage flash (MSF) have high initial costs and they demand large quantities of energy [2] thus, only large capacity desalination plants are economically feasible. The energy requirements are provided by fossil fuels with serious impact to the environment.

The Mediterranean region has a great renewable energy potential. Renewable energy, such as solar, wind and geothermal, can be utilized in small capacity desalination plants. In the last decades several studies have done to this direction. Most of them focus on the usage of solar energy through the routes of the photovoltaics and the solar stills, due to the high solar irradiation to the region.

Geothermal energy is also widely available in these countries. The geothermal water temperature varies between 80–110°C to the upper layers of the surface to 3251°C for a depth of 700–1400 m [3]. Studies have shown that low temperature geothermal waters in the upper 100 m may be a reasonable energy source for desalination [4,5]. An economic analysis of geothermal desalination in which sources of 110–130°C were considered, has shown that the cost of geothermal desalination is as low as the cost of large multi-effect dual purpose plants [4]. An experimental investigation was conducted with a desalination plant using the aero-evapo condensation process. The unit consists of a falling fill evaporator and condenser made of polypropylene. It was designed to work at low temperatures (70–90°C) and specially to use geothermal energy [6,7]. Two geothermal-powered distillation plants were installed one in France and one in the south of Tunisia using evaporators and condensers made from polypropylene at an operation temperature range of 60–90°C [7]. A study for a proposed project for the island of Milos, located in Cyclades Islands in Greece, has shown that the high geothermal potential of the island can be utilized with the use of an organic rankine cycle (ORC) turbogenerator electricity production unit, with an installed capacity of 300 kW, coupled to a multi-effect water desalination unit with an installed water production capacity of 80 t/h. The unit combines geothermal energy with an absorption chiller driven by the hot water at 85°C [3]. The study showed that the exploitation of the low enthalpy geothermal energy would help save the equivalent of 5000 TOE/y for a proposed plant capacity of 600–800 m^3/d of fresh water. Even in the case of limited geothermal energy, thermal desalination processes such as MED, thermal vapor compression (TVC), single-stage flash distillation (SF) and MSF can benefit greatly when coupled to geothermal sources by economizing considerable amounts of energy needed for preheating [8].

Membrane distillation (MD) is an emerging desalination technology, which can be driven by a thermal energy at low enthalpy (less than 363 K) as geothermal energy, and a fluidised bed crystalliser can ensure reduction of an important portion of hardness without significant loss of temperature [9]. A MD module would be coupled to a multiple effect distiller for pure water production. That study found that the best operating parameters are 85°C for a feed brine temperature at the evaporator inlet and a circulation flow of about 170 kg/h. Under these conditions, a GOR value of 3.7 and a water production of 16 kg/h may be reached. The integration of one membrane module distiller as a second step at the MED outlet permits an increase of distilled water production by about 7.5% and improvement of the energetic efficiency by practically 10%. Energetic analysis shows that MD can be driven by a low enthalpy sources as geothermal groundwater [10].

The humidification dehumidification desalination process is viewed as a promising technique for small capacity production plants. The process has several attractive features, which include operation at low temperature, ability to utilize sustainable energy sources, i.e., solar and geothermal, and requirements of low technology level [1]. A desalination process that can operate using low temperature heat such as geothermal energy and waste heat is the vacuum desalination. This technique takes advantage of a drop in the water boiling point at reduced pressure. This vacuum is created by a jet pump. By dropping the saturation pressure exerted on the seawater to about 0.05622 bar, a low temperature heat source can be used for boiling the seawater [11]. Another possibility which can be investigated is the use of high-pressure geothermal power directly as shaft power on desalination. Moreover, there are commercial membranes that withstand temperatures up to 60°C, which permits the direct use of geothermal brines for desalination [4].

2. Geothermal energy

Geothermal energy is one of the indigenous and environmentally friendly energy resources and has been used successfully for over three decades both for electricity generation and direct utilisation in many parts of the world. Geothermal energy has a number of positive features, which make it competitive with conventional energy sources and some renewable sources. These features include:

- It is a local energy source that can reduce demand for imported fossil fuels thus having a large positive impact on the environment.
- It is efficient and competitive with conventional sources of energy.
- The geothermal energy supply is without constraints imposed by weather conditions, unlike other renewable sources.
- It has an inherent storage capability and is best suited to base-load demand.

Geothermal resources are suitable for many different types of uses but are commonly divided into two categories, high and low enthalpy. High enthalpy resources (>150°C) are suitable for electrical generation with conventional cycles, low enthalpy resources (<150°C) are employed for direct heat uses and electricity generation using a binary fluids cycle. Atmospheric emissions are minor compared to fossil fuel plants. It has been estimated that a typical geothermal power plant emits 1% of the sulphur dioxide, <1% of the nitrous oxides and 5% of the carbon dioxide emitted by a coal fired plant of equal size. It should be noted that oil and gas exploration and development can also release carbon dioxide depending on the geological conditions encountered. However, some aquifers can produce moderate to high saline fluids, which are corrosive and a potential pollution hazard to fresh water drainage systems and ground water. Reinjection and corrosion management is therefore essential. High enthalpy geothermal sources, which are used for electricity generation, emit Carbon Dioxide in varying quantities depending on the geological conditions of different fields. The mode of operation (i.e., closed circuit or use of reinjection) will also affect the amount of Carbon Dioxide discharged to the atmosphere.

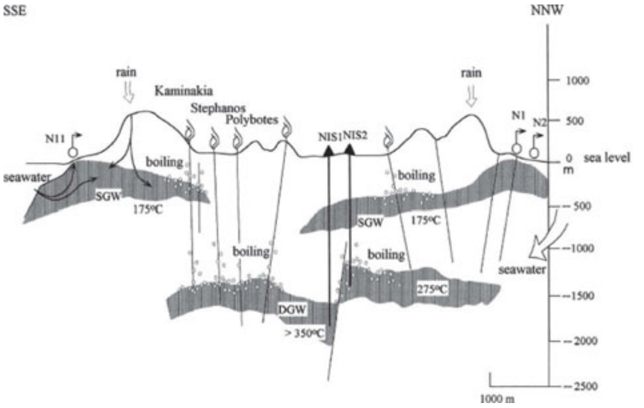

Fig. 1. Schematic hydrological model of thermal-fluid subsurface flow at Nisyros.

In the island of Nisyros data have been collected, by the Greek Energy Authority that indicates the existence of underground aquifiers at high temperatures (Fig. 1) [12].

3. Geothermal-med coupling

3.1. Multi effect distillation (MED) — Geothermal energy coupling

Geothermal energy is ideal for distillation processes and usually the multi effect distillation (MED) process (Fig. 2) is preferred due to the lower energy requirements in comparison to the multistage-flash distillation (MSF) process. Generally geothermal energy applications tend to be very site specific and design decisions for one location may not valid for another.

MED plants are typically built in units of 2000 to 10000 m^3/d. Some of the more recent plants have been built to operate with a top temperature (in the first effect) of about 70°C (158°F), which reduces the potential for scaling of seawater within the plant but in turn increases the need for additional heat transfer area in the form of tubes. Although the number of MED plants is still relatively small compared to MSF plants, their numbers have been increasing.

The cost of an MED plant heavily depends on the performance ratio. Capital and energy costs are significant factors. The main energy requirement is thermal energy. A plant operating with a performance ratio equal to 8, the thermal energy consumption is around 290 kJ/kg of produce water and electrical energy demand is 2.5–3 kWh/m^3. Total specific costs of the MED desalination technology are summarized in Table 1.

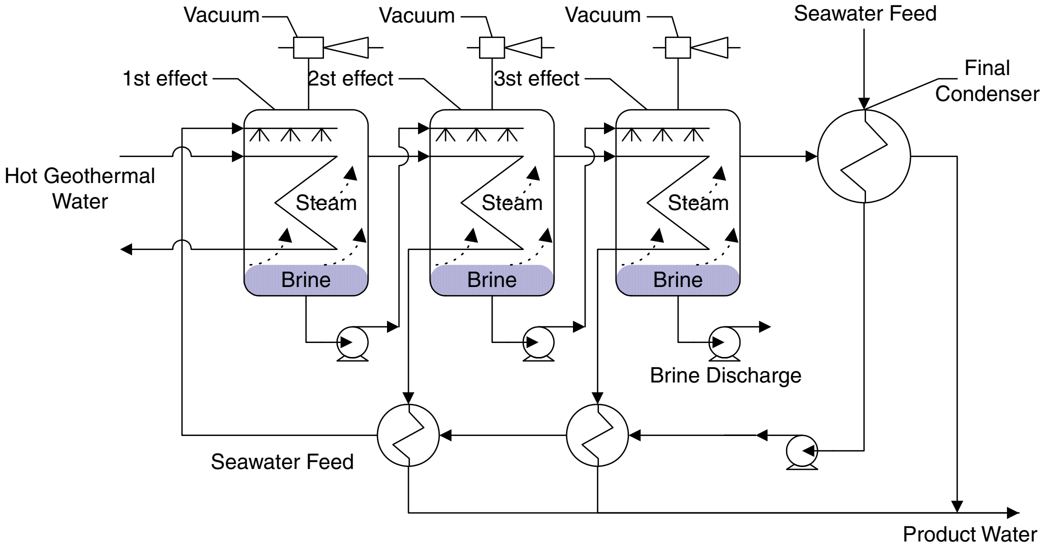

Fig. 2. Typical flow diagram of Multi Effect Distillation plant.

3.2. Multi effect distillation (MED) — Geothermal exergy analysis

There is an absolute theoretical minimum requirement of energy for a completely reversible process, which is independent on the mechanism, or the steps of the process, but it does depend on temperature, concentration and yield. This minimum energy requirement is about 0.8 kWh per m^3 of pure water from a 3.5% NaCl solution at 25°C based on the assumption that this concentration of pure NaCl is a close approximation to normal seawater [14]. This minimum assumes zero driving forces at every point of the process. The driving forces, resulting in thermodynamic irreversibility, are inherent in any distillation process. The thermodynamic irreversibilities of the process result in exergy (availability) losses. The MED and MSF processes operate with heat energy. It is important to consider the exergy of the heat source, which depends on temperature of the heat source (T_H) and the temperature of the heat sink (T_0). The relationship between minimum work ($W_{\min}$) and minimum heat ($Q_{\min}$) is:

$$W_{\min} = Q_{\min} \cdot \frac{T_H - T_0}{T_H} \quad \text{or} \quad Q_{\min} = W_{\min} \cdot \frac{T_H}{T_H - T_0} \qquad (1)$$

For a source temperature 120°C (393 K), sink (environment) temperature 20°C (293 K) and W_{min}=0.8 kWh/m^3 the minimum heat required (Q_{min}) per m^3 of pure water is 3.15 kWh. Steam is more often being used as a heat source. For saturated steam at 125°C the exergy is 640.8 kJ/kg or 0.178 kWh/kg so the minimum requirement under these conditions is 4.494 kg of steam per m^3 of pure water or 222.5 kg produce water per kg of steam. Thermal processes that rely on a change on water phase (MED, MSF), involve higher energy consumption than processes that do not require a change of phase (Table 2). However thermal processes can utilize geothermal energy or exhaust steam from turbines for electrical generation and can become economically attractive as compared to reverse osmosis (RO) energy cost. The MED process can utilize the low enthalpy geothermal resources (hot geothermal water 80–90°C) for the production of fresh water. Generally, water costs of less than 1 ECU per m^3 of product water are possible, which make the geothermal-MED coupling very attractive.

An MED desalination plan driven by hot geothermal sources with capacity of 500 m^3 of fresh water per day is

Table 2
Total specific costs of MED desalination processes [13]

Investment ECU/m^{3}d	Energy ECU/m^3	Consumable ECU/m^3	Labour ECU/m^3	Maintenance (ECU/m^3)	Total O & M costs (ECU/m^3)
900–1800	0.38–1.12	0.02–0.15	0.03–0.2	0.02–0.06	0.45–1.53

examined. For the evaluation of the desalination plant the following assumption are made:

Capacity (distillate produced)	$D = 500\ \mathrm{m^3/d}$
Feed seawater TDS concentration	$W_0 = 3.5\%$
Brine TDS concentration	$W_B = 1.25\ W_0$
Brine outlet temperature	$T_B = 40°\mathrm{C}$
Distillate outlet temperature	$T_D = 40°\mathrm{C}$
Geothermal water inlet temperature	$T_{GIN} = 80°\mathrm{C}$
Geothermal water outlet temperature	$T_{GOUT} = 60°\mathrm{C}$
Electrical energy consumption	3 kWh/m^3

From the mass and energy balance the following results derive:

Feed seawater flow rate	$M_0 = 1500\ \mathrm{m^3/d}$
Brine flow rate	$B = 1000\ \mathrm{m^3/d}$
Geothermal hot water flow rate	$M_G = 1875\ \mathrm{m^3/d}$

Thermal Energy Consumption per kg of distillate: 313.5 kJ/kg

The thermo-mechanical component of specific exergy (kJ/kg) was calculated from the following equation:

$$e_{TM} = C_p \cdot \left((T - T_0) - T_0 \cdot \text{In}\left(\frac{T}{T_0}\right)\right) \tag{2}$$

where C_p = 4.18 kJ/kg K, T = the temperature of the stream, T_0 = 298 K environmental temperature.

The specific chemical exergy for the brine blowdown and distillate were calculated from the following equations. [15]:

Brine:

$$e_c = f \cdot \frac{R}{MW} \cdot T_0 \cdot \frac{x_B \cdot x_0}{x_B - x_0} \cdot \text{In}\,\frac{x_B}{x_0} - f \cdot \frac{R}{MW} \cdot T_0 \cdot x_0 \tag{3}$$

Distillate:

$$e_c = f \cdot \frac{R}{MW} \cdot T_0 \cdot x_0 \tag{4}$$

where $f = 2$ is the fugacity coefficient, R = 8.31 kJ/kmole K, x_B the mole fraction in the brine, x_0 the mole fraction in the seawater, MW=18 the molecular weight of water.

Results from the application of the above equations are shown on Table 3. A schematic exergy diagram (Fig. 3) shows all the losses of the system.

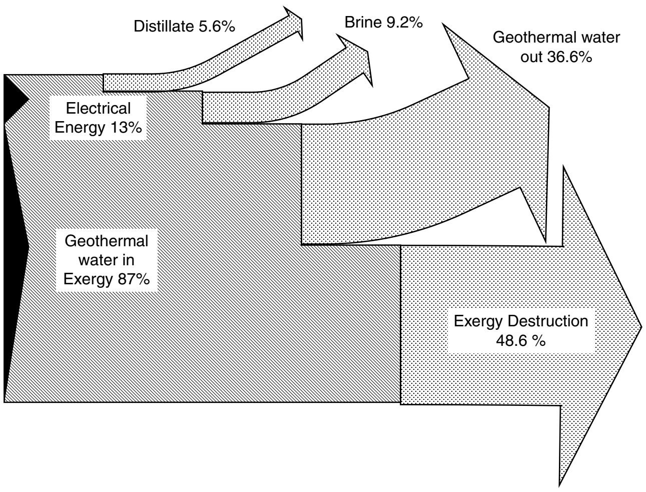

Fig. 3. Exergy balance of the MED desalination process.

Table 3
Energy consumption of the major desalination processes per m^3 of product [13]

Process	Primary energy	Exergy of steam (kWh/m^3)	Electric energy consumption (kWh/m^3)	Electric energy equivalent (kWh/m^3)
MSF	Steam	7.5–11	2.5–3.5	10–14.5
MED	Steam	4–7	~2	6–9
MVC*	Electricity	–	7–15	7–15
SW-RO	Electricity	–	4–6 with energy recovery 7–13 w/o energy recovery	4–6 with energy recovery 7–13 w/o energy recovery

*Mechanical Vapour Compression.

3.3. Geothermal-power plant-MED desalination coupling

The high enthalpy geothermal resources can be exploited by using a power plant-desalination scheme in order to increase the efficiency of the whole process. High enthalpy geothermal sources, which are used for electricity generation, emit various pollutants in the atmosphere in varying quantities depending on the geological conditions of different fields. Usually a H_2S removal process is needed (Stretford process). Tables 4 and 5 represent a partial list of the results obtained from the LCA study.

Table 4
Exergy balance of the MED desalination process

Stream	Specific exergy (kJ/kg)	Exergy (kW)
Geothermal water in	18.92	410.6
Electrical energy	10.8	62.5
Geothermal water out	7.97	–173
Distillate	4.6	–26.57
Brine	1.89	–43.8
Total exergy destruction		–229.7

High salt concentration on the geothermal fluid and the presence of H_2S may cause fouling and corrosion problems in a geothermal plant. A flash binary process can be used in order to avoid such problems (Fig. 4). The working fluid can be used as a heat source to the desalination process and thus to increase the overall efficiency of the plant.

Table 5
Resources used in a geothermal power plant [16]

Resources used	Units (tones/MW_e)
Feed Material	
Geothermal fluid (230°C)	4.72×10^5
Processing Materials	
Caustic soda process	
Sodium hydroxide	1.04
Stretford process	
Sodium ammonium polyvanadate	8.74×10^{-2}
Anthraquinone disulfonic acid (ADA)	2.44×10^{-2}
Iron catalyst (H_2O_2 supplemented) process	
Hydrogen peroxide	5.48
Ferrous sulfate and hydroxy acetic acid	1.52

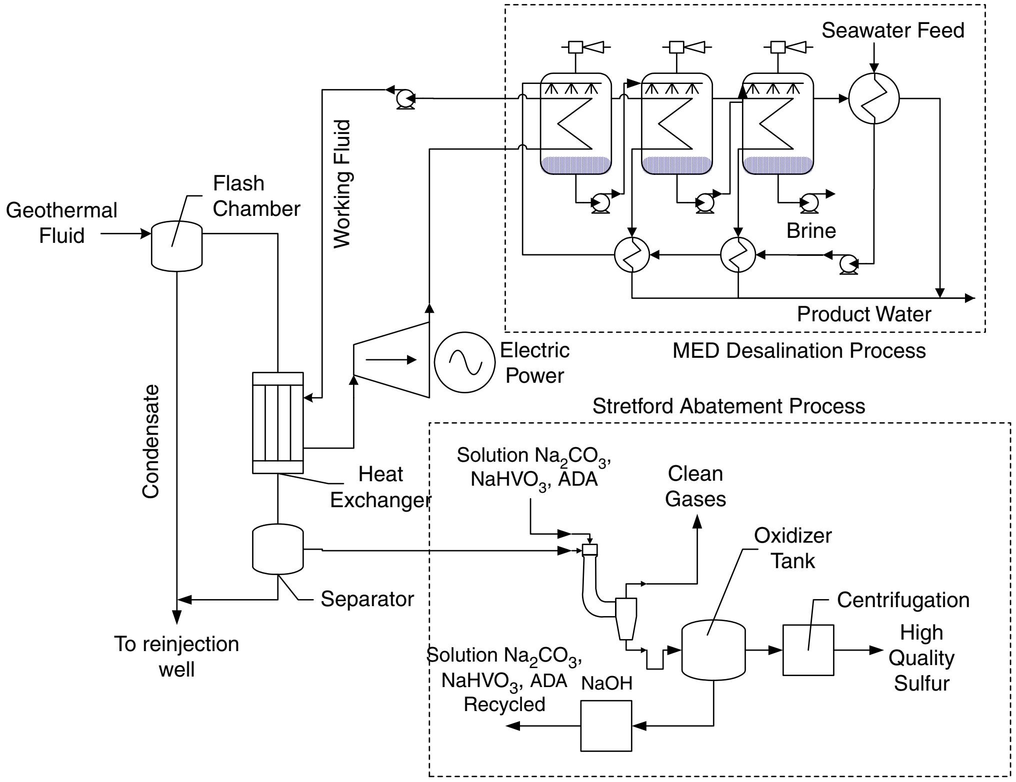

Fig. 4. Flash binary geothermal plant combined with MED process.

Table 6
Environmental residuals a geothermal power plant [16]

Environmental residuals (tones/MW_e)					
Air pollutants	Min	Max	Solid wastes	Min	Max
Hydrogen sulfide	8×10^{-2}	8×10^{-1}	Drilling mud (m^{-3}/MW_e)	1.03×10^{-1}	2.22×10^{-1}
Ammonia	3	3.08×10^{2}	Solid waste (from plant operation)		
Methane	1.96	8.2×10	Solids separated from fluid	7.8×10	
Carbon dioxide	1.23×10^{2}	1.23×10^{3}	Solids from H_2S abatement	3.2	
Arsenic	8.2×10^{-3}	5.48	Solids from scale removal	4.2	
Boron	2.06×10^{-1}	2.06	Recoverables/Recyclables		
Mercury	–	4.1×10^{-2}	Sulfur	6.86	6.86×10
Radon (Ci/MW_e)	2.1×10^{-1}	3.22×10^{-1}			
Benzene	4×10^{-1}				

4. Conclusions

Geothermal energy is ideal for distillation processes such as the MED. The geothermal energy supply is without constraints imposed by weather conditions, unlike other renewable sources. It has an inherent storage capability and is best suited to base-load demand. MED process seems to be ideal for the exploitation of low enthalpy geothermal resource for the production of potable water. The environmental impacts are negligible during the operation of the plant. MED process can be combined with a geothermal driven power plant in order to increase the overall efficiency by utilizing the waste heat. The use of fossil fuels is reduced dramatically and this leads to the increase of sustainability of island regions.

Symbols

T_H — temperature of the heat source
T_0 — temperature of the heat sink
W_{min} — minimum work
Q_{min} — minimum heat
D — Capacity (distillate produced) (m^3/d)
W_0 — Feed seawater TDS concentration (%)
W_B=1.25 W_0 — Brine TDS concentration (%)
T_B — Brine outlet temperature (°C)
T_D — Distillate outlet temperature (°C)
T_{GIN} — Geothermal water inlet temperature (°C)
T_{GOUT} — Geothermal water outlet temperature (°C)
M_0 — Feed seawater flow rate (m^3/d)
B — Brine flow rate (m^3/d)
M_G — Geothermal hot water flow rate (m^3/d)
e_c — The specific chemical exergy
f — the fugacity coefficient
x_B — the mole fraction in the brine
x_0 — the mole fraction in the seawater

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