

Low-Temperature Solar-Thermal Multi-Effect Evaporation Desalination Systems

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ABSTRACT: As part of a project investigating the productive use of saline land and the development of sustainable desalination systems, the production of potable water from seawater or brackish water using desalination systems powered by low-temperature solar-thermal sources, including salinity-gradient solar ponds and evacuated tube solar collectors, has been studied. A Visual Basic - Excel computer model of solar-powered multi-effect evaporation (MEE) desalination processes was developed to determine the technical and economic feasibility of the system. A small-scale three-effect evaporation desalination system powered by a solar pond, capable of producing up to 2,300 litres of fresh water per day, has been designed using the model. The system has been manufactured and commissioned, and has operated effectively at a first-effect vapour temperature of about 68°C, which is ideal for heat delivery from a solar pond. One of the advantages of the MEE - Solar pond arrangement is the possibility of utilising the discharged concentrated salt solutions from the MEE system for commercial salt production, or constructing additional solar ponds to support additional desalination capacity. The key design and operating parameters controlling the cost of fresh water – distillate production, recovery ratio, thermal energy and solar collection area – were determined from the computer simulation and compared with experimental results. A good agreement between the experimental data and the modelling results has been obtained.

Keywords: Solar desalination; multi-effect evaporation; solar pond; renewable energy; modelling.

NOMENCLATURE

Symbol Description [Units]

M _{sp}	mass flow rate of heating fluid [kg/s]
C _{psp}	specific heat at constant pressure [kJ/kg.°C]
T _{sp}	solar pond supply stream temperature [°C]
T _{spr}	solar pond return stream temperature [°C]
U _{E1}	overall heat transfer coefficient [kW/m ² .°C]
A _{E1}	heat transfer surface area of the evaporator [m ²]
LMTD	logarithmic mean temperature difference [°C]

1. INTRODUCTION

Shortages of freshwater caused by changing weather patterns are truly a global problem, particularly felt today in arid regions. Over a quarter of the world's population are suffering from inadequate fresh water supply [1]. Desalination technologies have been implemented to meet growing demands for fresh water. Australia is the driest continent on earth battling both drought and land salinity, and yet has abundant access to seawater and brackish ground water.

There are currently several proven methods of desalting water, the most common large-scale processes being Multi-Stage Flash (MSF), Multiple-Effect Evaporation (MEE), and Reverse Osmosis (RO) [2]. Despite technological improvements, desalination systems continue to be intensive fossil-fuel consumers and contribute to increased levels of greenhouse gases. With rising oil prices and increasing supply instability, together with international requirements for greenhouse gas emission reduction, lowering traditional energy requirements for desalination by making use of renewable sources such as solar energy and waste heat is essential [3]. An attractive solution, especially for areas with abundant solar radiation, is to couple a low-temperature multi-effect evaporation (MEE) process with a salinity-gradient solar pond or other type of solar thermal system.

In this paper, as part of a broader study of solar-thermal desalination systems, a 3-effect MEE system, with a daily production of 2,300 litres, coupled to a solar pond is presented. A theoretical analysis of the MEE system has been completed and Visual Basic - Excel models developed to estimate key parameters for a range of different conditions and configurations. The governing mathematical equations were derived from mass balances, heat energy balances, and heat transfer characteristics. The results from the modelling have been

used to design the 3-effect system, which employs the forward-feed configuration and a submerged tube evaporator system in each effect. The critical operating parameters are determined from the computer simulation and compared with the first experimental results obtained.

2. SALINITY-GRADIENT SOLAR PONDS (SGSP)

A salinity-gradient solar pond (Figure 1) is a shallow pond with a salt gradient. Solar radiation that reaches the bottom of the pond is trapped in the lower region and stored since convection currents are suppressed. Solar ponds combine solar energy collection with long-term storage to provide reliable heat at temperatures between 50 and 90 °C. Solar ponds have a low capital cost since they are based on locally available low-cost materials, and can be incorporated into salinity mitigation schemes [4, 5].

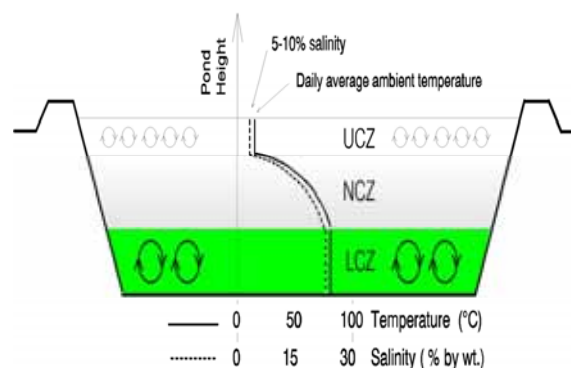


Figure 1: Solar pond salinity and temperature profiles.

The possible coupling arrangements between solar technologies and desalination systems are shown in Table I. A number of solar-thermal heat sources can be used with MEE desalination technologies. The system investigated in this paper is an MEE system coupled with a salt-gradient solar pond for desalting brackish water. One of the advantages of this solar pond-MEE arrangement is the possibility of utilising the discharged concentrated salt solutions from

the MEE system for commercial salt production, or constructing additional solar ponds to support additional desalination capacity and therefore eliminating environmental impacts.

Table I: Solar-Thermal Coupling Options.

Solar Technology	Desalination Systems		
	MSF	MEE	RO
Flat Plate / Evacuated Tubular Collectors	*	*	
Concentrating Parabolic Collectors (Co-generation –electricity and heat)	*	*	*
Salinity-Gradient Solar Ponds (SGSP)	*	*	
Photovoltaic			*

3. THE 3-EFFECT MEE SYSTEM

A schematic of the overall 3-effect MEE system that has been designed and constructed is shown in Figure 3. A central design aim has been to maximise the effective reuse within the system of the heat initially put into the seawater from the solar thermal source so that the specific energy of the system (thermal energy input per unit volume of fresh water) is minimised. Minimising the specific energy yields an economic benefit by minimising the required area of solar collector.

The system therefore employs a forward-feed configuration whereby hot liquid brine in each effect is transferred via a valve as the feed into the next effect, thus making optimum use of the energy content of the brine at each stage. Three submerged-tube evaporators are used each with a tube bundle in the lower part of the shell to provide the heating surface. The tubes are covered completely with the saline water to be desalted. The demister is housed above the heating tubes in the disengagement space. The feed saltwater, which is part of

the total intake of seawater or saline groundwater, is partially preheated in the condenser by the vapour coming from the last effect. The remaining cooling seawater is stored in tanks for later use. The feed is then further heated progressively by the feed preheaters before it enters the first effect. In the first evaporator, the in-flowing seawater is heated to its boiling temperature and partly evaporated by boiling. Heating is performed by passing hot water from the salinity-gradient solar pond inside the tube bundle in this first effect. The partial evaporation of the saltwater occurs by a nucleate pool boiling process. The vapour produced in the first evaporator is used as the heat source in the second evaporator operating at a lower pressure. The remaining brine enters the second effect as the feed. The brine leaving the second effect enters the last effect as the feed and so on. The use of feed preheaters maximises the heat recovery process, hence improving the thermal specific energy consumption.



Figure 2: Experimental Forward-Feed MEE.

Submerged tube evaporators are simpler to construct and operate, and cheaper, than the more commonly employed falling-film evaporators. However, submerged evaporators are slightly less energy efficient, and may have a higher rate of calcium sulphate scale formation if operated at high temperature and salinity [6].

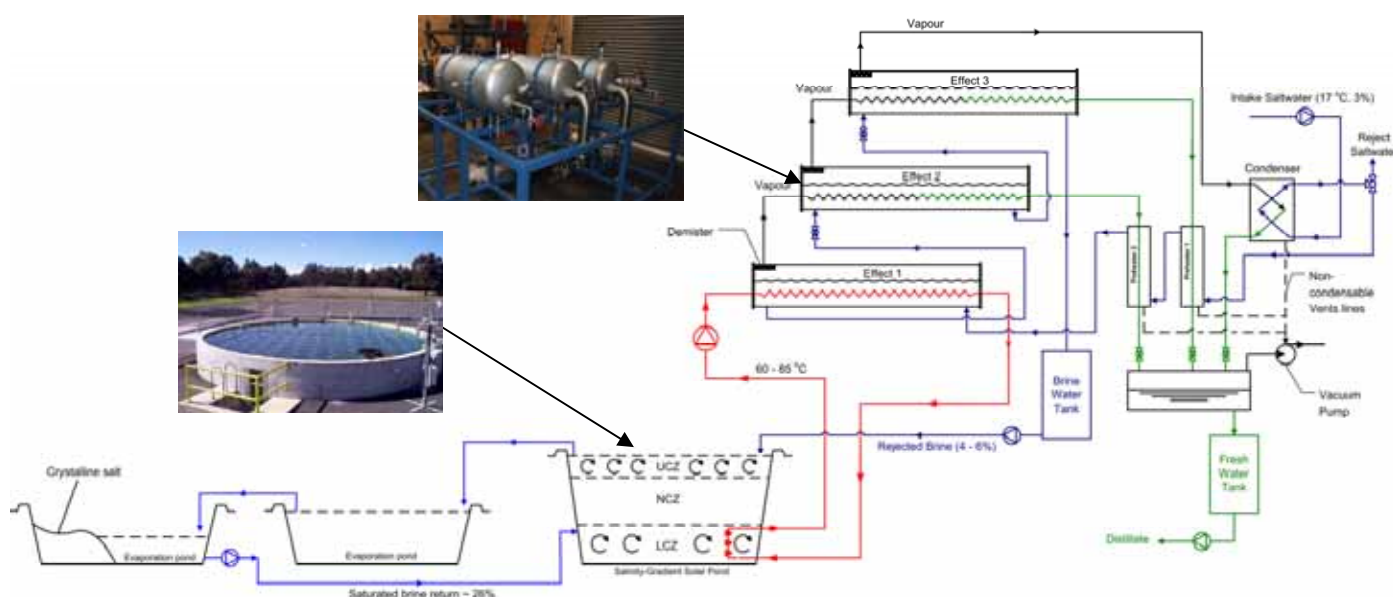


Figure 3: Schematic of 3-Effect Forward-Feed SP-MEE system.

Conventional MSF systems must be operated under fairly constant heat input conditions to avoid any change in water level due to fixed orifices and weirs that control inter-stage pressures and water levels [7]. In conventional MSF/MEE systems, the heat source (usually steam) temperature is fixed, whereas the intake seawater varies in temperature depending on the season. In our case, the inland saline groundwater temperature is relatively constant whereas the heat input from the solar pond varies.

Non-condensable gases can accumulate in condensing zones and reduce the heat transfer. Insufficient venting leads to an accumulation of these gases with adverse effects on the heat transfer, performance, and material lifetimes. Excessive venting results in unnecessary vapour losses and a higher energy consumption of the venting system. In the present 3-effect MEE system, non-condensable gases are withdrawn from the vapour condensation space in each condenser/preheater by a simple vent connected to a vacuum pump line. The vents are adjusted depending on the rise and fall of the boiling temperature in each effect.

The main specifications of the 3-effect MEE system are summarised in Table II.

Table II: MEE Technical Specifications.

Number of effects	3
Evaporator shell diameter (m)	0.36
Evaporator heat transfer area (m ²)	1
Condenser shell diameter (m)	0.15
Condenser heat transfer area (m ²)	1
Preheater heat transfer area (m ²)	0.25
Intake saltwater temperature (°C)	17
Feed salinity (ppm)	30,000
Evaporator / condenser length (m)	1
Vacuum Pressure System [Liquid Ring Pump] (kPa.abs)	7

4. MEE PERFORMANCE RESULTS

4.1 Distillate Production

The distillate production rate of the 3-effect MEE system derived from the computer simulation is presented as a function of the supply temperature from the solar pond in Figure 4. The computer simulation assumes no thermal losses and ignores the partial suction of vapour due to the non-condensable vents. The distillate production rate varies between 0.55 and 1.57 Litres/min. The temperature difference

between the heating fluid and the boiling temperature in the first effect varies between 10 and 19°C, depending on the heating fluid temperature. The boiling temperature difference between the effects varies between 6.5 and 13°C. The boiling temperature in the first effect is designed to be around 70°C. The last effect operates at a temperature in the range 37 to 40 °C. Figure 5 shows the experimental distillate production, from the three different effects of the MEE system when working at 70 °C.

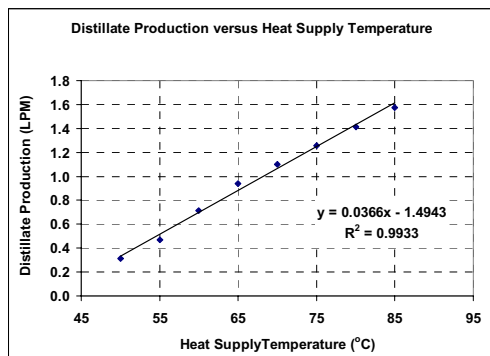


Figure 4: Simulated distillate production rate at different supply temperature.

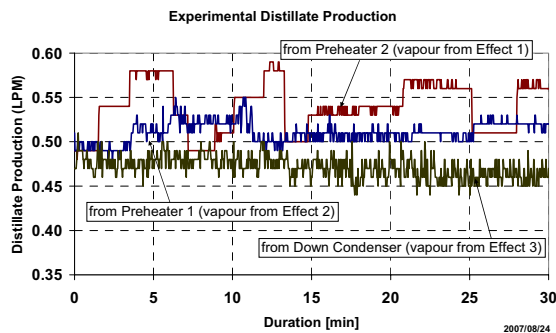


Figure 5: Experimental distillate production rate from different effects when operating at 70°C.

Figure 6 below shows the total distillate production.

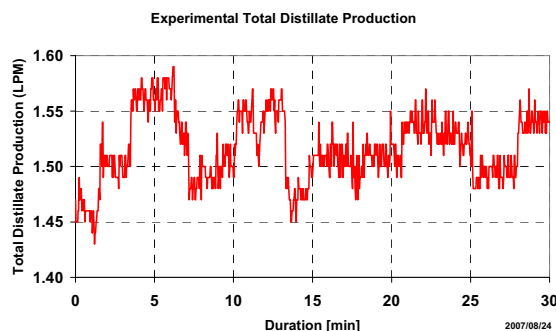


Figure 6: Experimental total distillate

4.2 Heat Transfer Coefficients

The overall heat transfer coefficient of the evaporator in the first effect, U_{E1} , was calculated using the following equation

$$m_{sp}Cp_{sp}(T_{sps} - T_{spr}) = U_{E1}A_{E1}(LMTD)_{E1} \quad (1)$$

The measured overall heat transfer coefficient for the three effects and the condenser is presented in Figure 6 below.

The measured overall heat transfer coefficient in the first effect, U_{E1} , is around 1200 W/m².°C as compared to the measured values of 2700 and 2500 W/m².°C for the second and last effect respectively. U_{E1} is quite low due to insufficient hot water flow in the tube bundle of the first evaporator. By increasing this flow rate and hence increasing the turbulence, the heat transfer would improve and the first effect would operate at a higher temperature.

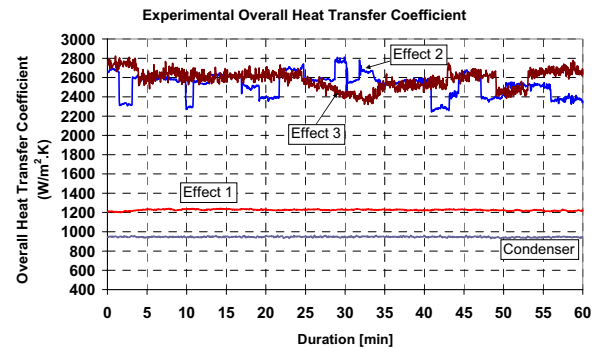


Figure 6: Experimental values for overall heat transfer coefficient.

In a multi-effect submerged-tube evaporator, the boiling saltwater has limited movement around the heating surface as a result of convection currents and the continuous rise of the vapour bubbles. Consequently, this gives a low heat transfer coefficient on the boiling side and causes scale accumulation on the hot tubes. In a falling-film tube evaporator, the heat transfer coefficient is higher and the contact time is lower [8].

4.3 Comparative Analysis

Table III below shows the summary of the predicted and measured performance values of the 3-effect MEE system. The difference in the distillate production rate is due to the low overall heat transfer coefficient in the first effect. The overall heat transfer coefficient used in the modelling is around $2200 \text{ W/m}^2\cdot^\circ\text{C}$ and non-condensable and heat losses effects are neglected. The daily water production rate is about $1.9 \text{ m}^3/\text{day}$. The system yields a high recovery ratio of over 50%.

Table III: Comparative Table (Predicted and Experimental Performance)

Performance Parameters	Simulation Results	Experimental Results
Total Intake		
Seawater flow rate (LPM)	19.4	15.1
Heating water flow rate (LPM)	37.2	22.3
Heating fluid water supply temperature ($^\circ\text{C}$)	86	86
Feed flow rate (LPM)	2.63	2.55
Feed Salinity (ppm)	32,100	32,100
Distillate flow rate (LPM)	1.49	1.32
Distillate Salinity (ppm)	assumed salt free	9
Specific Thermal Energy Consumption ¹ (kJ/kg)	925	968
Recovery Ratio ²	56.6%	51.8%

1. Heat energy input per litre of fresh water produced

2. Rate of production of fresh water divided by the rate of saline water input, times 100%.

Figure 7 below compares the distillate production obtained from the modelling and the experimental data for different heat supply temperature. As shown in the figure, there is a close match between the modelling predictions and the experimental results. However, the computer simulation

tends to over predict the distillate production and this is due to the modelling assumptions (no thermal losses and negligible effect due to the non-condensable vents).

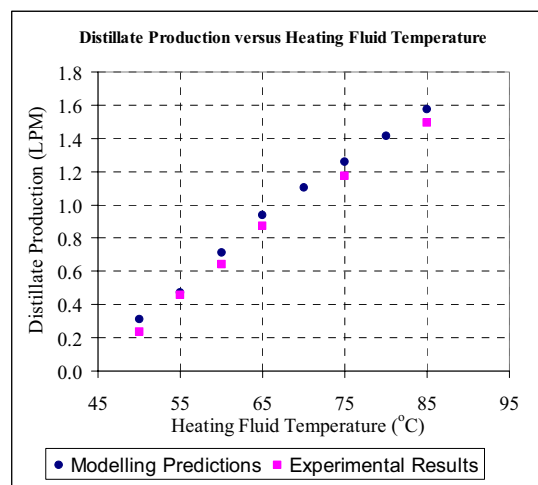


Figure 7: Distillate comparative analysis

5. ECONOMIC EVALUATION

The values of the economic parameters used to estimate the water production cost are listed in Table IV.

Table IV: Economic parameters adopted to calculate water cost

Pre-treatment (\$/m ³)	0.020
Manpower (\$/m ³)	0.082
Maintenance (% of plant Cost)	2
Conventional Electricity (\$/kWh)	0.068
Solar Pond efficiency	15%

The unit costs of the fresh water produced for different plant capacities are given in Table V. These vary depending on the type of salt used and cost of liner in the solar pond. They decrease with increasing desalination plant capacity as a result of economies of scale. Published figures [9], which provide average cost data for evaporators, tanks and pumps of different sizes, were used to estimate the capital cost of heat exchangers. The cost of water for a plant producing over 650 kL/day of fresh water would be around \$1.7/kL if bittern

(mainly magnesium chloride) is used as the salt and a cheap liner (500 microns thick) is used in the solar pond.

Table V: Preliminary evaluation of water cost

Performance indicator	3-effect expt. MEE	Potential commercial MEE system	
		12 effects ^a	12 effects ^b
Fresh water production [lower value at 60°C; higher at 85°C]	900 - 2300 litre/day	50-130 kL /day	260-650 kL /day
Specific (thermal) energy (kJ/kg)	880 - 960	250 - 275	250-275
Recovery rate	35 - 55%	35 - 58%	35-58%
Area of solar pond ^c (m ²)	720	11,800	58,900
Yearly fresh water production	630 kL	36 ML	180 ML
Unit costs on lifecycle basis ^d (\$/kL)	18 - 22	3.4-5.1	1.7-3.4

a. Length of evaporator: 3 metres; Evaporator shell diameter: 0.6m

b. Length of evaporator: 6 metres; Evaporator shell diameter: 0.9m

c. Sizing of solar pond is based on the amount of heat required by the desalination system in summer when the average total global radiation is around 20.2 MJ/m²-day. The solar pond is 2.2m deep.

d. Present value of all costs over the lifetime of the unit (25 years), at 5% real discount rate, divided by the total production of fresh water over that time. All costs are in US dollars (exchange rate: 1 AUD ~ 0.854 USD). Unit costs do not include cost of delivery.

For comparison purposes, the quoted cost of fresh water from the reverse osmosis (RO) plant now operating in Perth, Australia is about \$1.0/kL [10]. This plant draws electricity from the WA grid and the costing is based on the normal grid electricity

prices. A wind farm at Emu Plains elsewhere in the state inputs zero emission power into the grid to offset the power consumed by the desalination plant. The marginal costs of the wind power are higher than the average grid prices so in effect the real cost of the fresh water produced is much higher than the cost quoted above. The RO desalination plant for Botany Bay, Sydney, Australia, proposed in 2005 and later put on hold by the NSW Government, was stated as being able to supply fresh water at \$1.23/kL, but again this cost was based on current NSW grid electricity prices, and not on zero emission sources of electricity [11]. The cost of water delivered from the proposed RO desalination plant in Wonthaggi, Victoria is estimated to be around \$2.57/kL [12].

6. CONCLUSION

A simulation model of a 3-effect MEE system has been developed and used to design a small-scale forward-feed system capable of producing up to 2300 litres/day of fresh water. The results obtained show that the 3-effect MEE unit using a solar pond as the heat source requires about 900 kJ to produce a litre of fresh water and can convert up to 55% of the input salty water into fresh water. A commercial unit of this type with 12 effects and a fresh water production capacity of 180 Megalitres per year in a location with high solar radiation can be expected to produce fresh water from saline ground water at a cost of between \$1.7 and \$3.4 per kilolitre, and most importantly with very low greenhouse emissions. This is still a relatively low-capacity desalination plant compared to the size of RO plants currently operating such as the 45 GL/y plant in Perth, Western Australia, so that much larger solar thermal MEE plants may be expected to have even lower unit costs than the preliminary estimates presented in this paper. Further detailed work is nevertheless required to

refine these costings. The indications are thus that the cost range for solar-thermal MEE desalination systems is competitive with the other main zero-emission desalination options. The costs of solar thermal MEE is likely to be less than that of a reverse osmosis (RO) system powered by a photovoltaic system, and comparable with that of an RO system using wind power from a site with a high mean wind speed.

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