A SOLAR-ASSISTED SEA WATER MULTIPLE EFFECT DISTILLATION PLANT 15 YEARS OF OPERATING PERFORMANCE (1985-1999)

Ali M. El-Nashar
Water and Electricity Authority, Abu Dhabi, UAE

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Contents

1. Introduction

In the remote and isolated coastal areas of the Arabian Gulf region, potable water is very scarce and the establishment of a human habitat in these areas strongly depends on how such water can be made available. These areas are normally far from the conventional supply markets for liquid fuels or natural gas, a fact which makes the transportation of such fuels an expensive proposal. Fortunately, these areas are blessed with a high solar radiation intensity which makes the use of this renewable energy source for the desalination of sea water an attractive idea.

In order to study the technical and economic potential of using solar energy for desalination in the remote areas of the UAE, a demonstration plant was designed and built as a part of a joint research project between the Water and Electricity Department (WED) of Abu Dhabi, UAE, and Japan's New Energy Development Organization (NEDO).

The plant was commissioned during the last quarter of 1984 and went into operation in January 1985. The aim was to obtain long-term performance data which would enable a proper assessment of its potential for water supply in remote areas. The objective of this paper is to review the degree of plant performance, degradation and major maintenance activities during plant lifetime (1985-1999).

2. Basic Design Concept

2.1. General Plant Description

The solar desalination plant is located at Umm Al Nar, about 20 km north east of Abu Dhabi city. It is designed for an expected yearly average freshwater production of 80 m^3 day^{-1}. A simplified schematic of the plant is shown in Figure 1 and a photographic view is shown in Figure 2.

A bank of evacuated tube solar collectors, whose orientation with respect to the sun has been optimized to collect the maximum amount of solar radiation, is used to heat the collector fluid (water) to a maximum temperature of about 95°C. The effective collector absorber area of the bank is 1862 m^2. The collector bank consists of 1064 collector panels manufactured by Sanyo (type STC-BH250LBA and STC-BH250RBA) whose standard specification is given in Table 1.

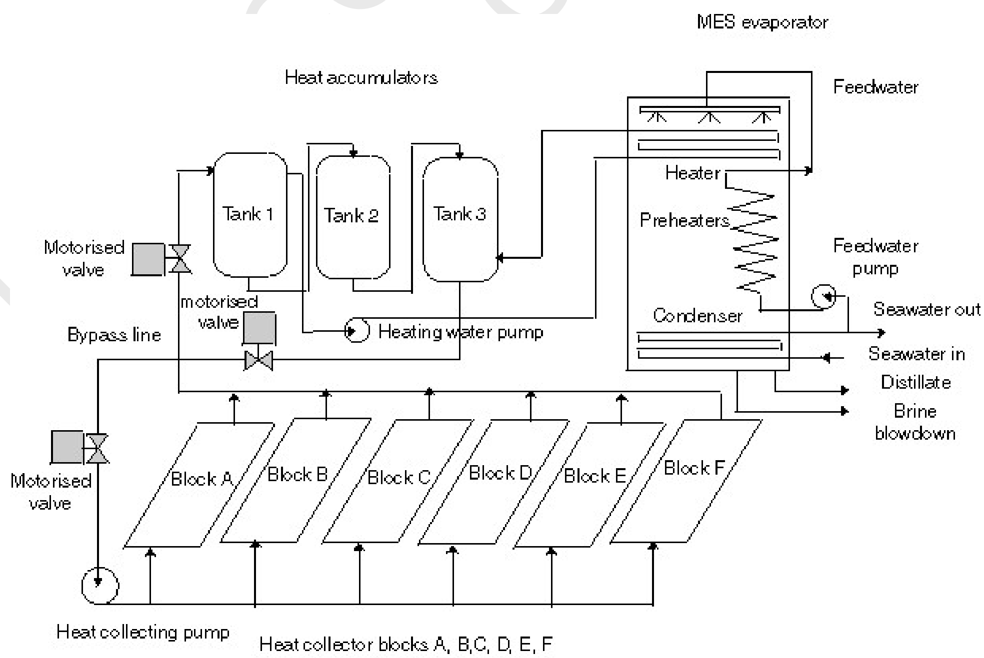

Figure 1. Schematic of the solar desalination plant.

Selective coating	Absorptivity $\alpha \geq 0.91$,emissivity$\varepsilon \leq 0.12$
Absorber area	1.75 m^2
External dimensions	2860 mm×985 mm×115 mm
Net weight (empty)	64 kg
Operating weight (full)	67.5 kg
Circulation flow rate	700-1800 l h^{-1}
Maximum operating pressure	6 bar

Table 1 Specifications of each evacuated tube collector panel.

Figure 2. Photographic view of the solar desalination plant.

The heat collecting water leaving the collector bank flows into the top of the heat accumulator system which has a total capacity of 300 m^3 and consists of three vertical cylindrical tanks connected in series and thermally insulated (tanks #1, 2 and 3 in Figure 1). The heat accumulator system is of the thermally stratified type where, by virtue of density variation between the top and bottom layers, the higher temperature water is located in the upper region of the accumulator tank while the lower temperature water occupies the lower region. The low temperature water is drawn from the bottom of tank #3 and is pumped through the collectors by the heat collecting pump which has a capacity of 80 $m^3 h^{-1}$ at 26 m head. The capacity of the heat accumulator system is specified to be able to provide the required thermal load for the evaporator for about 16 h after sunset, which makes it possible to operate the evaporator day and night all year round. Only during extended overcast periods or hazy days such as when sandstorms prevail do we expect the plant to shutdown due to insufficient thermal energy storage.

The heat collecting water is drawn from the top of accumulator tank #1 by the heating water circulating pump and is forced to flow into the tube bundle of the first effect of a multi-effect stack (MES) evaporator. This evaporator is of the horizontal-tube, thin-film type, and is designed for a rated distillate output of 120 m^3 day^{-1} from sea water having a salinity of 55 000 ppm (TDS). By transferring heat to the cooler brine flowing on the outside of the tube bundle of the first effect, the heating water is cooled down before being discharged and returned back to the accumulator.

The MES evaporator has 18 effects, stacked one on top of the other, with the highest temperature effect (the first effect) located at the top of the stack, and the lowest temperature effect (the 18th effect) at the bottom. The 18 effects are actually arranged in a double-stack configuration, where effects 1, 3, …, 17 are in one stack, and effects 2, 4, 6 … 18 in the second. The double-stack arrangement is incorporated into a single evaporator vessel. In addition to the 18 effects, the evaporator has 17 feedwater preheaters and a final condenser designed to condense the vapor generated in the 18th effect. For more information on the design features of this type of evaporators, please refer to the papers by Takada and Drake (1983) and Takada (1976).

2.2. Design Specifications

The following climatic and seawater conditions are used in the design of the plant:

Ambient air temperature	average 30°C, minimum 7°C, maximum 48°C.
Rainfall	18.1 mm $year^{-1}$-390.1 mm $year^{-1}$
Relative humidity	10 per cent (minimum)-100 per cent (maximum)
Wind speed	5 m s^{-1} (for collector design), 30 m s^{-1} (for structural design)
Solar radiation	5000 kcal $(m^2 \cdot day)^{-1}$
Sea water temperature	35°C
Sea water salinity	52 000 ppm TDS

The following design parameters are used in the design of the MES evaporator:

Rated capacity	130 m^3 d^{-1}
Number of effects	18
Number of preheaters	17
Performance ratio	12.4
Heat rate	42.4 kcal kg^{-1} distillate
Sea water temperature	35°C
Heating water temperature	99°C

2.3. Evaporator Heat Transfer Coefficient

Except for the first effect, all other effect in the MES evaporator have heat being transferred in the evaporator tube bundle in such a way that condensing vapor flows inside the tubes and brine boiling outside the tubes. Because of this design feature, this system is characterized by a high heat transfer coefficient. The correlation for the overall heat transfer coefficient used in the design of the evaporator (in kcal h^{-1} m^{-2} °C) which was developed by the manufacturer (Sasakura Engineering Co.) (ENAA and WED 1986) is as follows

$$U = 3200(-0.4678 + 0.05T_B - 0.5\cdot 10^{-3}T_B^2 + 0.17\cdot 10^{-3}T_B^3) \qquad (1)$$

where T_B is the brine temperature in any effect (°C).

2.4. Tube Dimensions, Heat Transfer Areas and Materials

Table 2 shows the tube dimensions, surface area and tube and tubesheet materials for the evaporator, preheater and condenser bundles. Except for the first effect (which is also called the heater), the tube diameter for all tube bundles is 16 mm. The first effect bundle has 15 mm tubes. The tube bundles have multi-pass arrangement for the vapor which condenses inside the tubes. All the evaporator bundles with the exception of the first effect have identical surface areas of 61.3 m^2; the first effect has a surface area of 24.1 m^2. Each of the 17 preheaters has a surface area of 33.8 m^2. Tube material is 70/30 Cu-Ni for the first effect, Al-Br for all subsequent effects, and titanium for all the preheater and condenser tube bundles. The evaporator shell is made of steel lined with synthetic rubber to prevent any contact between saline water and shell material.

	First effect (heater)	Effects 2-13	Effects 14-18	Condenser	Preheaters 1-17
Tube OD×thickness (mm)	15×1	16×1	16×1	16×1	16×0.5
Tube length (mm)	3050	3050	3050	3400	3400
No. of passes	4	4	3	4	6
No. of tubes per effect	168	400	400	112	198
Surface area per effect (m^2)	24.1	61.3	61.3	19.1	33.8
Tube material	70/30 Cu-Ni	Al-Br	Al-Br	Titanium	Titanium
Tube sheet material	70/30 Cu-Ni	Naval brass	Naval brass	Titanium	Titanium

Table 2. Tube dimensions, surface areas and material of tube bundles.

3. Performance During Commissioning Tests

Commissioning tests (ENAA and WED 1986; El-Nashar and Qamhieh 1991) for each of the plant's major equipment took place during September and October, 1984. Some of the results obtained are shown in the following sections.

3.1. The MES Evaporator

Figure 3 shows the effect of the heating water inlet temperature on the distillate production when the heating water flow rate is maintained constant. It can be seen that the evaporator's distillate production is quite sensitive to variations in the heating water temperature where increasing heating water temperature gives rise to higher production. Increasing the heating water flow rate for a given value of heating water temperature also results in higher production. It should be noted that the feed water flow rate is always maintained at the preset value of 17.5 $m^3 h^{-1}$ by a cascade controller. Increasing the heating water temperature results in an increase in the temperature of each effect, which, in turn, results in an increase in vapor production by each effect due to higher heat transfer coefficients.

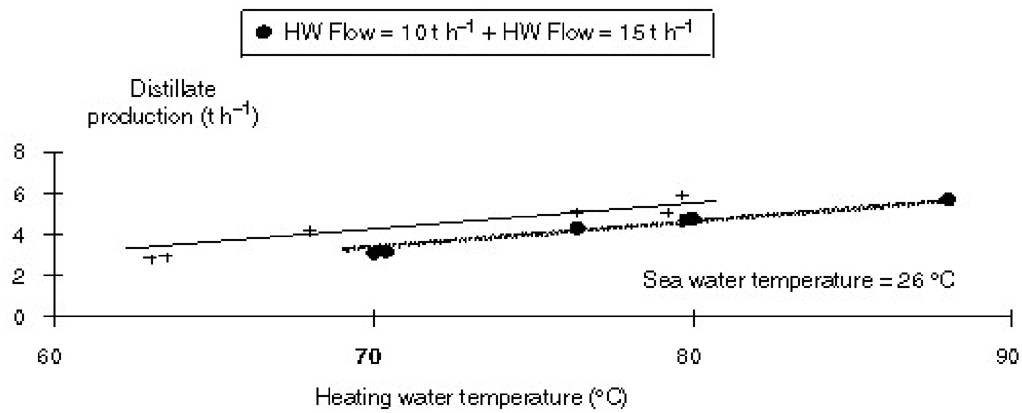

Figure 3. Effect of the heating water temperature on the distillate production.

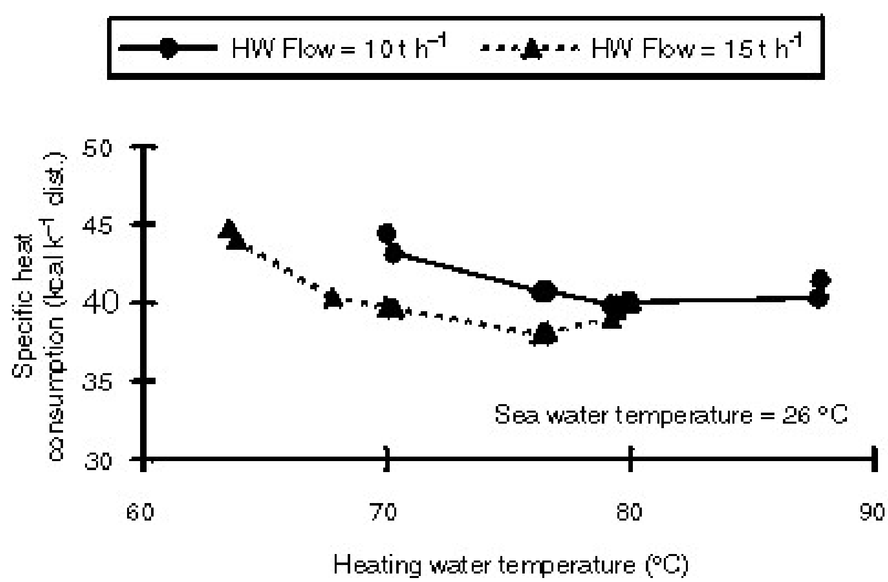

Figure 4. Effect of heating water temperature on the specific heat consumption.

Figure 4 shows the effect of heating water temperature on the specific heat consumption for constant heating water flow rates of 10 $m^3 h^{-1}$ and 15 $m^3 h^{-1}$. As can be seen, increasing the heating water temperature results in a reduction in the specific heat consumption which reaches a minimum value that depends on the heating water flow rate. For the smaller heating water flow rate (10.0 $m^3 h^{-1}$), the minimum specific heat consumption was 40.0 kcal kg^{-1} dist. occurring at a heating water temperature of about 80°C, whereas this minimum drops to 38.0 kcal kg^{-1} dist. at 76.3°C for the higher heating water flow rate (15.0 $m^3 h^{-1}$). Beyond the optimum heating water temperature corresponding to the minimum specific heat consumption, any increase in the heating water temperature results in an increase in the specific heat consumption.

The initial decrease in the specific heat consumption (which corresponds to an increase in the performance ratio) associated with the increase in the heating water temperature can be ascribed to an increase in the inter-effect temperature difference. The increase in the specific heat consumption beyond the optimum heating water temperature may be attributed to excessive steam losses through the brine overflow lines in each effect.

The heat transfer mechanism in the first effect evaporator is different from all other effects. In the first effect, heat is transferred from the heating water flowing inside the tubes of the first effect tube bundle to the boiling seawater flowing on the outside surface as a thin film (El-Nashar 1990). The heat transfer mechanism in the evaporator effects #2 to #18 involves simultaneous vapor condensation inside the tube and brine boiling outside the tubes. This is why the first effect evaporator is called "the heater" to distinguish it from the other effects.

The design and measured average values of the OHTC for the evaporator are shown in Figure 5. The design values are those obtained from Eqn 1. As can be seen, the design equation predicts the OHTC reasonably well.

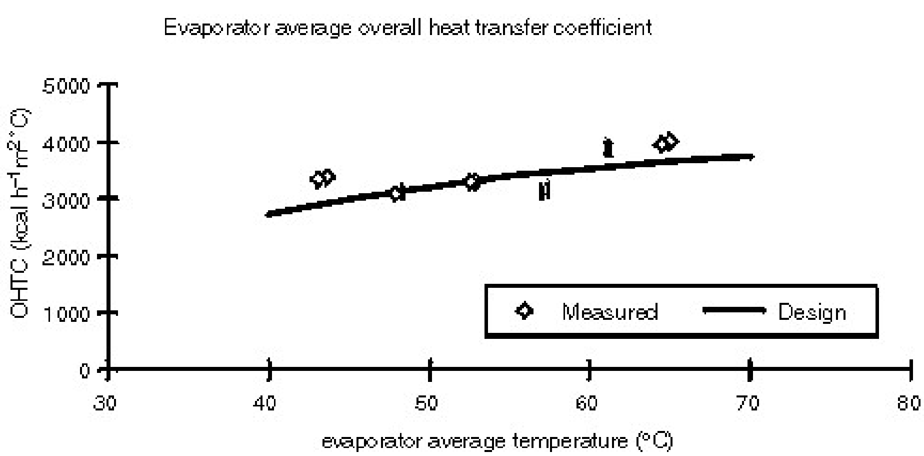

Figure 5. Average overall heat transfer coefficient of evaporator #2-#18.

The variation of several operating parameters during a typical summer day is shown in Figure 6. The heating water temperature varies during the day according to the state of charge of the heat accumulator (El-Nashar 1989). During night hours, the heat accumulator is being gradually discharged by supplying heating water to the evaporator since the solar collecting field is out of operation. The heating water is cooled down in the evaporator heater then returned back to the accumulator. Therefore, over the night period, a gradual decline in the heating water supply temperature takes place resulting in a gradual drop in distillate production. After sunrise, the solar collector field is put into operation thus collecting heat which is supplied to the accumulator. When the amount of heat collected becomes greater than the amount of heat supplied to the evaporator, the accumulator water temperature starts to rise thus causing the heating water supply temperature to increase resulting in an increase in distillate production. This is clearly shown in the figure. At around 15:00 h, the solar radiation intensity drops down to a level at which the amount of heat collected becomes just equal to the amount of heat supplied to the evaporator. This is the point where the heating water supply temperature, and closely in phase with it, the distillate production, reach their maximum values beyond which they start to drop.

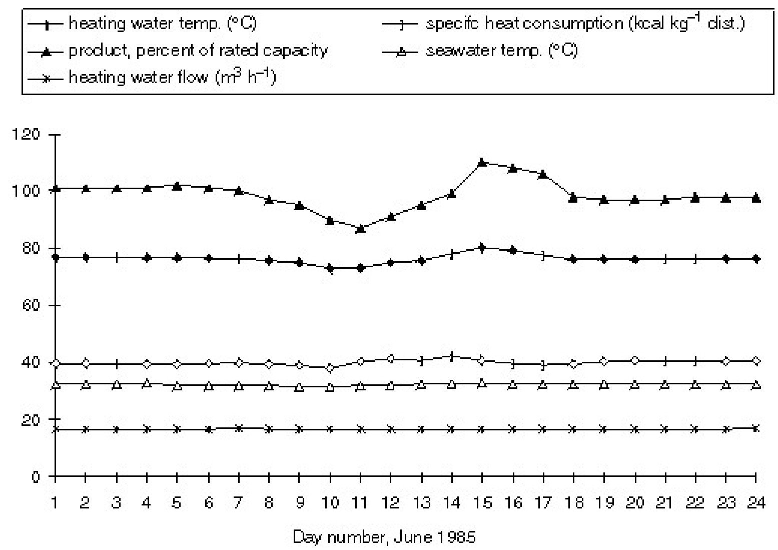

Figure 6. Evaporator performance from the daily report for 01/06/1985.

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Biographical Sketch

Ali M. El-Nashar received the B.Sc. (Mech. Eng.) from Alexandria University (Egypt) in 1961 and Ph.D. (Nuclear Engineering) from London University (UK) in 1968. He has been a faculty member at several universities in Egypt, UK and USA and was appointed professor of mechanical engineering at Florida Institute of Technology (USA) and Mansoura University (Egypt). He was a research fellow at Clemson University (USA) during the period 1971 to 1976. He has worked as consultant for different industrial and UN organizations among which Dow Chemical Co. (USA), Ch2M-Hill Co. (USA), Science Application Co. (USA), UNEP, Technology International Co. (USA). He is member of the ASME, ISES and IDA and editor of the International Desalination and Energy journals. He has worked at the Research Center of the Abu Dhabi Water and Electricity Authority (UAE) as manager of the desalination and cogeneration section which pioneered development work on solar desalination for ADWEA for 20 years. He has been associated with the International Centre for Water and Energy Systems, Abu Dhabi, UAE.