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Seasonal effect of dust deposition on a field of evacuated tube collectors on the performance of a solar desalination plant

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Abstract

This paper reveals the results of a study aimed at identifying the seasonal influence of dust deposition on a large field of evacuated tube collectors associated with a multiple-effect distillation plant on the performance of the plant. The system is located near the city of Abu Dhabi, UAE, and the results are therefore relevant to this region. Seasonal dust measurements were made on the system and a mathematical model of the dust effect is incorporated within the SOLDES program, which predicts the performance of such systems, taking into consideration the prevailing dust influence and the frequency of collector cleaning. It was found that dust deposition has a strong seasonal effect on the plant performance with the strongest influence taking place during the summer months of June, July and August during which sand storms prevail in the plant location. It was found that dust deposition can cause a monthly drop in glass tube transmittance of 10–18%. The drop in transmittance of the glass tubes due to dust deposition can cause a large drop in plant production. For example, for a transmittance decrease from an initial value of 0.98 (clean glass condition) to a low value of 0.6, corresponding to a very dusty glass condition, production drops from 100% to 40% of the clean collector production level. The weekly cleaning frequency was found to result in the maximum annual water production for the particular location under consideration. It was found that dust deposition decreases the specific water production (m^3 of water per kJ of incident solar radiation) and increases the specific power consumption (kWh per m^3 water).

Keywords: Dust effect; Solar desalination; Evacuated tube collectors; Performance degradation

1. Introduction

Dust accumulation on the glazing of solar thermal collectors associated with distillation plants for seawater desalination is one of the main natural causes for performance degradation. This is particularly so for plants in operation in remote desert locations subject to sand storms where the air is laden with fine sand particles. Dust deposition on flat plate collectors has been studied by several authors, e.g., Goossens and Van

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Kerschaever [1], El-Shobokshy and Hussein [2], Sayigh et al. [3], Hegazy [4], Nimmo and Seid [5] and Garg [6]. El-Nashar [7] studied the influence of dust deposition on the performance of evacuated tube collectors on a large field of collectors and found that accumulated dust on this type of collector can result in a substantial reduction in collector efficiency. The effect of dust deposition on the transmittance of the glazing material was also studied by Mastekbayeva and Kumar [8] at a tropical climate condition and found that the transmittance dropped from 87.9% to 75.8% over a period of 30 days. The airborne particles in the atmosphere were found to affect the amount and properties of the radiation finally reaching the collectors (see Al-Hassan [9]). Outdoor measurements on glazing transparency were performed by Nahar and Gupta [10] and Bonvin [11]. Hegazy [4] studied dust accumulation on glass plates with different tilt angles and measured the transmittance of the plates under different climatic conditions in Minia, Egypt, over a period of one month. The degradation in solar transmittance during this period was found to depend on the tilt angle of the glass plates with a maximum value when the plate is in a horizontal position and minimum value when it is vertical. Measurements made by Sayigh et al. [3] of dust accumulation on a tilted glass plate located in Kuwait were found to reduce the transmittance of the plate by an amount ranging from 64% to 17% for tilt angles ranging from 0 to 60°, respectively, after 38 days of exposure to the environment.

Goossens and Van Kerschaever [1] carried out wind tunnel experiments to find the effect of wind velocity and airborne dust concentration on the drop of photovoltaic (PV) cell performance caused by dust deposition on the cells. It was found that the deposition of fine dust particles on PV cells significantly affect the performance of such cells.

The solar desalination plant situated in Abu Dhabi, UAE, was used to study the effect of dust accumulation on the performance of the plant. This is a demonstration plant that is located on the site of the Umm Al Nar cogeneration plant (about 20 km northeast of Abu Dhabi city) that went online in 1984 and is operated by the Research Center of Abu Dhabi Water and Electricity Authority (ADWEA).

The aim of this study is to evaluate the effect of seasonal dust deposition on the solar collector field and the frequency of collector cleaning on the performance of the solar desalination plant.

2. Solar desalination plant

A simplified schematic of the plant is shown in Fig. 1 and a photo is shown in Fig. 2. The plant consists of a field of evacuated tube collectors, a thermally stratified heat accumulator consisting of three tanks and a multiple-effect distillation (MED) unit for seawater desalination. The collector field consists of 1064 panels of evacuated tube collectors, each having a selective absorber area of 1.75 m^2, thus making the total absorber area 1862 m^2. The collector field is divided into 76 collector arrays each consists of 14 collector panels connected in series. The field is divided into six blocks named A, B, C, D, E, and F as shown in Fig. 3. All arrays in each block are connected in parallel to the block inlet and outlet headers. A photo of a single collector panel is shown in Fig. 4 and its specifications are listed in Table 1.

The MED unit consists of 18 effects (arranged in two vertical stacks) in which the seawater or its brine is made to boil under vacuum at different boiling temperatures ranging from the highest at the first effect (top effect) to the lowest at the 18th effect (bottom effect). Preheated seawater is sprayed on the outside surface of the first effect evaporator tube bundle in which hot water from the accumulator flows through the tubes. Part of the seawater is boiled off and the remaining brine cascades down to the following effects where it is sprayed on the second tube bundles and vapor

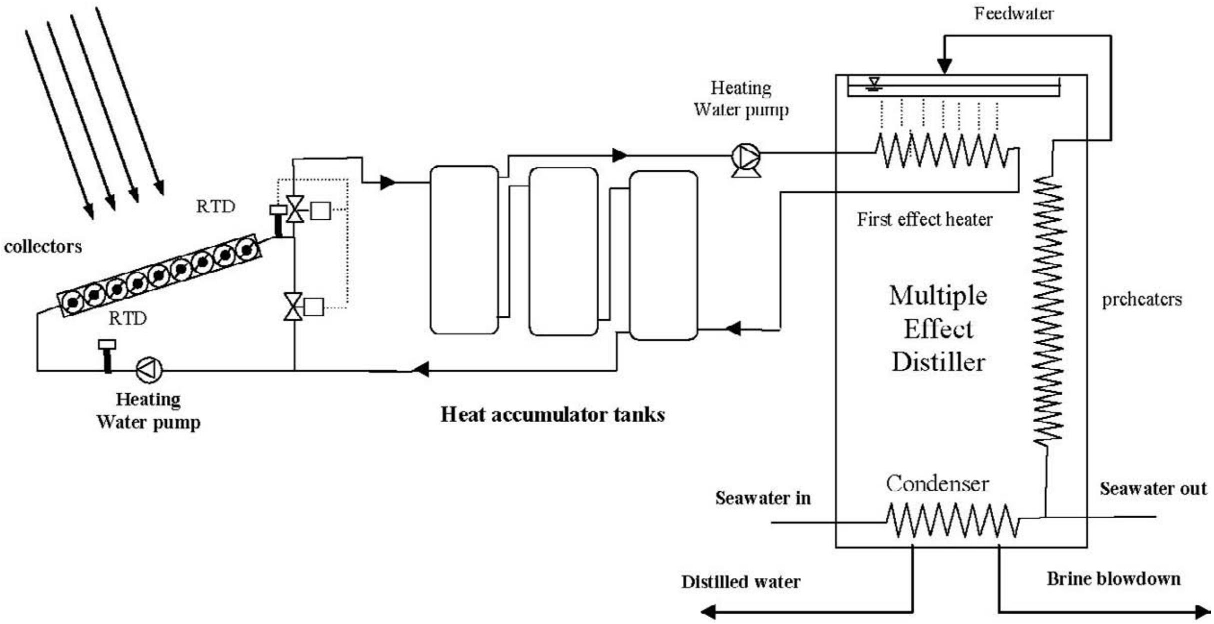

Fig. 1. Schematic of the solar desalination plant in Abu Dhabi.

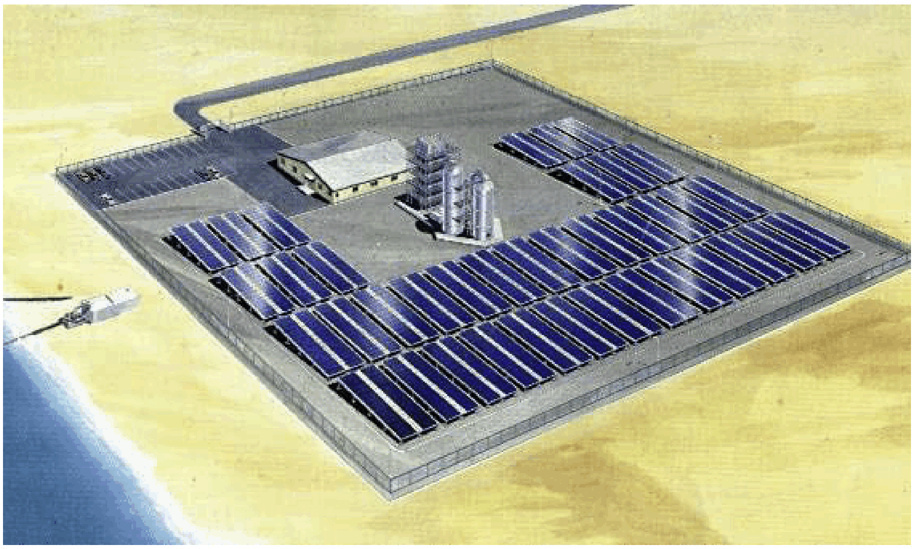

Fig. 2. Artist's rendering of the solar desalination plant in Abu Dhabi.

generated in each effect by using the vapor generated in one effect as a heat source for the following effect.

The plant was designed to operate in an automatic fashion where the heat collecting system (consisting of the collector field, by-pass line and heat collecting pump) is controlled by a solar controller and the MED evaporator is controlled by the heat accumulator temperatures. The operation of the heat collecting system depends on the

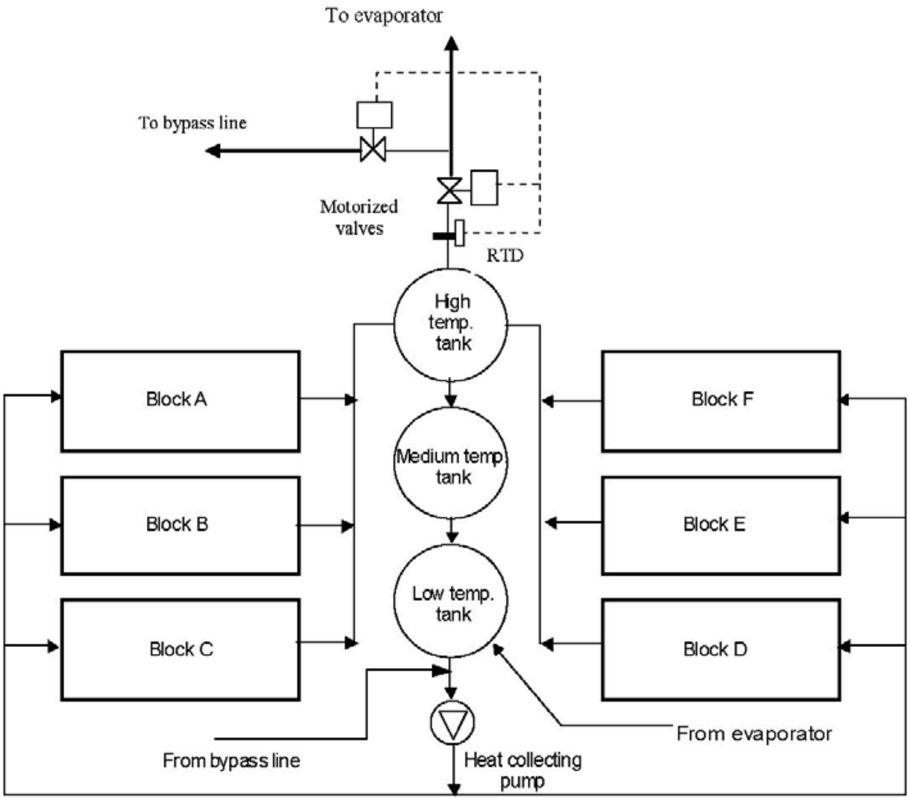

Fig. 3. Schematic of the solar collector field of the solar desalination plant in Abu Dhabi.

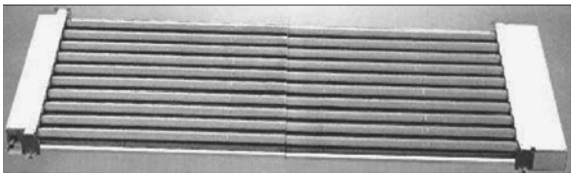

Fig. 4. Photo of a single collector panel (Sanyo STC-BH250LB).

Table 1
Specifications of a single collector panel

Item	Specification
Selective coating	Absorptivity $\alpha \geq 0.91$ Emissivity ≤ 0.12
Absorber area, m^2	1.75 m^2
External dimensions, mm	2860×985×115
Net weight, kg	64
Flow rate, L/h	700–1,800
Max. operating pressure, bar	6

intensity of solar radiation as well as the temperature of the accumulator tank. The operation of the evaporator depends on two temperatures measured using RTDs and located at the medium-temperature and high-temperature accumulator tanks. These two RTDs are connected to setpoint controllers which would allow the evaporator to initiate its start-up sequence (when it was previously shut down automatically) when the medium temperature rises above the corresponding setpoint. When the water temperature in the hot water tank drops below the corresponding setpoint value, the evaporator starts its shutdown sequence and the evaporator will continue in this mode until the medium temperature rises above the corresponding setpoint.

Since the collector field represents the only source of thermal energy to the evaporator, the condition of the collectors is expected to affect substantially the performance of the whole plant. The purpose of this paper is to find the effect of dust deposition on the glazing of a commercial evacuated tube collector field on the performance of an operating solar desalination plant that utilizes this collector field to supply thermal energy to a seawater distillation plant of the MED type.

3. Measurements and data acquisition system

3.1. Data acquisition system (DAS)

The main components of the data acquisition system (DAS) are shown in Fig. 5. They consist of two data loggers (Yokogawa Thermodac-32 and Yokogawa Thermodac-3), one online PC (NEC model 8001mkII), one data analysis PC (NEC model 8801mkII), one control room printer (NEC-8023C) and one report generating printer (NEC-8023C). The Thermodac-32 data logger has the capacity of 32 input signals that can be a combination of 1–5 VDC signals, 4–20 mA signals, and pulse signals. The Thermodac-3 has the capacity of 20 input Pt100 resistance signals from RTD probes. Every 15 min data are stored in the memory every hour; the four items of data collected during the previous hour are transferred to the online computer via the RS 232C interface. The results of the mean value of the four data values are calculated and displayed every hour by the online computer.

The DAS has the following functions:

- Samples data at 15-min intervals.
- Calculates hourly average values once per hour

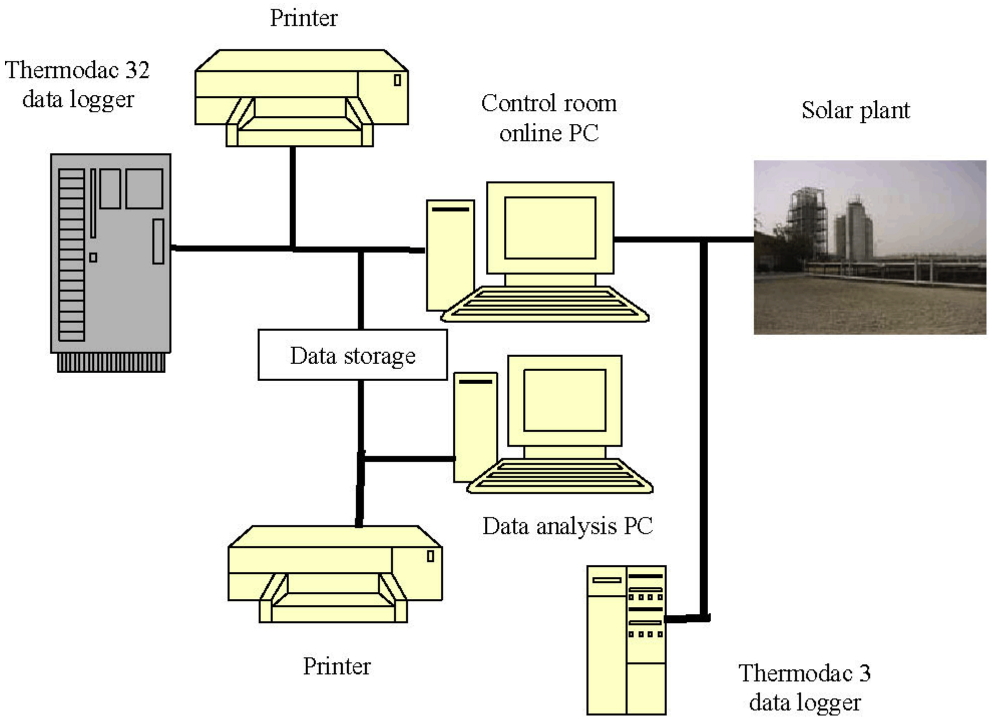

Fig. 5. Data acquisition system.

- Records data on CD at even hours (i.e. 8:00, 10:00, 12:00,…)
- Prints a summary report every 12 h.
- Makes daily, weekly and monthly reports.

The following measurements were carried out during plant operation:

- Weather data (solar radiation, relative humidity, ambient temperature and seawater temperature)
- Collector water temperature at several locations around the collector bank (inlet and outlet to Block A, inlet and outlet to Block F, inlet and outlet to the whole collector bank).
- Heat accumulator water temperature at several locations (water temperature at the bottom, middle and top of each of the three accumulator tanks).
- Vapor temperature at different effects of the MED unit (effects 1, 4, 7, 10,13, 16 and 18).
- Feedwater temperature at the entrance and exit of the preheater train.
- Heating water temperature at the inlet and exit of the heater (first effect) tube bundle.
- Flow rate measurements of heat collecting water, heating water, feedwater, distilled (product) water, and condenser cooling water.
- Heat collected from Block A, Block F and the total collector bank (consisting of the six blocks A, B, C, D, E, and F).
- Pump running hours (heat collecting pump and product water pump).
- Electrical energy consumption of the whole plant

3.2. Transmittance measurement

Dust deposition on the collector field is expected to affect the transmittance of the evacuated glass tubes by reducing the intensity of solar radiation impinging on the absorber plates. Since it is difficult to measure the transmittance of the evacuated glass tubes of the actual collector field, sample glass tubes (un-evacuated) of identical material, diameter and wall thickness to the actual glass tubes were used to measure the transmittance. The sample glass tubes are exposed to the same weather condition as the collector field in the plant and they are also exposed to the same cleaning frequency as the collector field since they are cleaned whenever the collector field is cleaned. It was then assumed that the dust condition on the sample tubes is almost identical to that of the actual glass tubes.

Fig. 6 shows how transmittance of the sample glass tube was measured using two solar sensors. Measurements were taken at 12:00 mid-day during sunny days with the solar sensors attached near the ends of a support plate. The support plate is inserted inside a sample glass tube such that one solar sensor is located about the middle of the sample glass tube while the other is outside the tube. The support plate is tilted at the same angle as that of the collector absorber plates. The voltage outputs of the two sensors are measured simultaneously using two identical millivoltmeters which have been previously calibrated. The corresponding solar radiation intensity on a tilted surface inside and outside the tube was estimated and the transmittance was calculated using the equation:

$$\tau = C_s \frac{V_2}{V_1}$$

where V_1 is the voltage of the outside sensor, V_2 is that of the inside sensor and C_s is a calibration constant.

Two sample glass tubes were used, one to simulate the dust condition of each of collector blocks A and F; they are referred to as sample tubes A and F, respectively. Block F was used as a reference clean block by exposing it to frequent cleanings to make sure that it remained always clean. The frequency of cleaning of block A, on the other hand, was varied according to the requirement of the test program. The two sample tubes are cleaned at exactly the same time their corresponding collector blocks are cleaned. Thus,

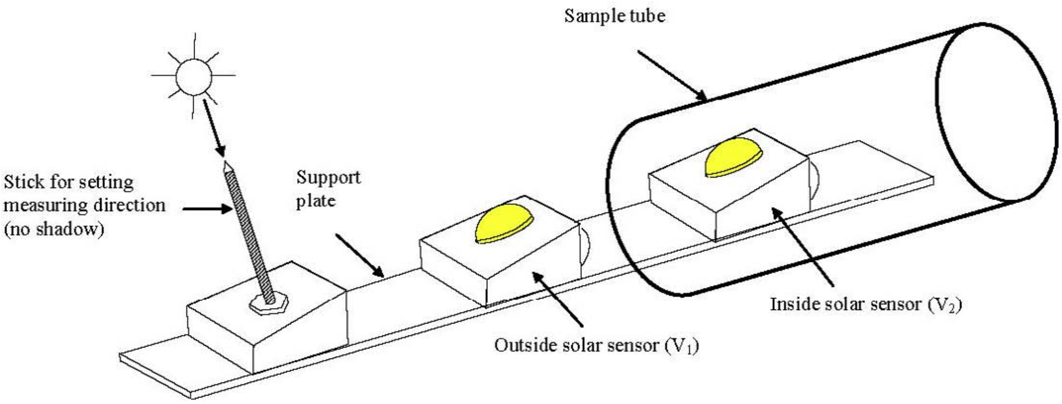

Fig. 6. Measuring the transmittance of a sample glass tube.

whenever blocks A and F are cleaned, their corresponding sample tubes are also cleaned. Two individual test programs were conducted. In the first test program, block A (and sample tube A) was cleaned once per month at the first day of month. In this program, the main objective was to find the seasonal variation of monthly dust accumulation of block A and the corresponding variation in its heat collection performance. In the second program, the effect of long-term dust accumulation on the performance of block A was investigated by allowing this block to operate for a whole year without being cleaned. Each of the test programs was carried out over a period of one year.

3.2. Cleaning of Blocks A and F

Collector blocks were cleaned from dust accumulation by using part of the fresh water produced by the MED evaporator using a high-pressure water spray. The water spray was produced by a positive displacement high-pressure plunger pump having a discharge pressure of 50 atm and a flow rate of 18 L/min. It was measured that the washing of each collector panel (absorber area of 1.75 m^2) consumes about 6 L of water and takes about 20 s to clean. It was estimated that about 6.4 m^3 of water would be needed to clean the whole collector field and that would take about 6 hours to do this job.

3.3. Heat collection measurement

Each of blocks A and F are provided with two, three-wire RTD probes for measuring the inlet and outlet collector fluid temperatures and a vortex flow meter (accuracy 1.0% plus 0.1% of full scale) for measuring the flow rate of collector fluid through each block. These measurements were carried out on a continuous basis during the daytime when the heat collecting pump is in operation. From these temperature measurements, the instantaneous values for the heat collected from each block can be estimated. Integrating these quantities over the daily operating period of the heat collecting pump would yield the daily amount of heat collected by each block.

The RTD electrical resistance signals monitored by these two probes are converted into 1–5 V DC signals by resistance-to-voltage converters. These two voltage signals along with a third one representing the heat collecting water flow rate were supplied to a programmable computing unit which measures the instantaneous heat collected by each of blocks A and F. The signals representing the heat collecting water inlet and outlet temperatures as well as the instantaneous heat collected are also supplied to a data logger (Thermodac-32 Data Acquisition System, Eto Denki).

4. Dust model

The amount of dust accumulated on the glass tube depends on the season of the year. Summer months are characterized by sand storms and lack of precipitation and dust can readily accumulate on the glass tubes during these months. Fig. 7 shows the end-of-month transmittance for each month when the glass tube is cleaned thoroughly at the beginning of each month. At the beginning of the month, when the glass tube is clean, transmittance reaches an initial value of 0.98 and as the outside of the glass tube is allowed to accumulate dust over a month, the transmittance gradually falls until it reaches its lowest value at the end of the month. At this point the sample tube is cleaned again at the beginning of the following month. As can be seen, the monthly drop in transmittance varies from a low of 2% to a high of 16%. It varies from 2–4% during winter (November–April), with the lowest during the month of January, and varies from 6–16% during the summer (May–August) with the maximum during the month of July.

Based on the measured values of transmittance over a period of one year, the monthly drop in the transmittance of the glass tube can be correlated to the month number (January =1, February =2,..) as follows:

$$\Delta\tau_m = A_m \times m^2 + B_m \times m + C_m \quad (1)$$

where $\Delta\tau_m$ is the drop in transmittance of the glass tube during month *m*, A_m, B_m, C_m are constants for each month, *m* is the month number (for January, m =1; February, m =2, etc.). The values of the monthly constants A_m, B_m, C_m are evaluated from actual experimental data using the least square technique.

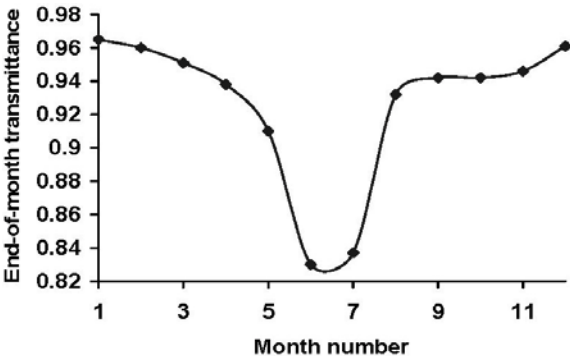

Fig. 7. End-of-month transmittance of glass tube when the tube is cleaned at the first of each month and left to accumulate dust throughout the month.

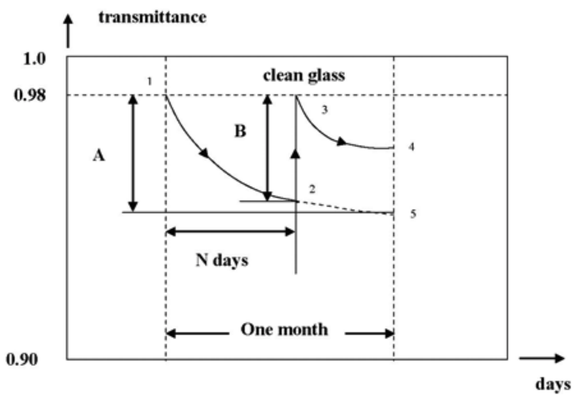

Fig. 8. Drop in transmittance during a typical month.

Fig. 8 shows how the transmittance varies for a typical month. It is a graph of the transmittance of a glass tube versus the day number for a typical month. It assumes that the glass tube has been cleaned on the first day of the month and again after a period of *N* days has elapsed. During the first day of the month (point 1), the transmittance has an initial value of 0.98. At the end of the period, the transmittance drops to point 2 due to dust accumulation. After cleaning, the transmittance jumps to its initial value (point 3) and subsequently drops to point 4 at the end of the month. Referring to the total drop in transmittance for a typical month as A and the drop during the period of *N* days as B (see figure), the ratio (B/A) has been shown by Sayigh et al. [3] to follow an exponential form:

$$\frac{B}{A} = 1 - \exp(-\alpha \times N) \quad (2)$$

where α is a constant that has a specific value for each month. The transmittance after N days can therefore be estimated by reference to Fig. 8 as:

$$\begin{aligned}\tau_N &= 0.98 - B \\ &= 0.98 - A \times \left[1 - \exp(-\alpha \times N)\right]\end{aligned} \quad (3)$$

5. Results

Fig. 9 shows the monthly average daily solar radiation ratio and the monthly average daily production ratio for clean collector glass tubes. This is a hypothetical situation in which the collectors are assumed to be absolutely clean with no dust allowed to deposit on them. The monthly average daily ratio is defined as the ratio between the average daily value for a particular month of the year to the yearly average daily quantity. It can be seen that, as expected, the monthly average distillate production follows the pattern of daily solar radiation with the maximum daily production occurring during the month of June that is characterized by the highest solar radiation intensity.

The effect of collector glass transmittance on the plant annual production ratio (defined as the annual plant production with dusty collectors divided by the ideal annual production with clean collectors) is shown in Fig. 10. The data plotted here are the output of a number of runs of the SOLDES program using the specifications of the Abu Dhabi solar desalination plant. The data of the production ratio can be fitted to a polynomial of second degree using the least square technique:

$$\frac{M_d}{M_d^{\max}} = -1.523\tau^2 + 3.937\tau - 1.402 \quad (4)$$

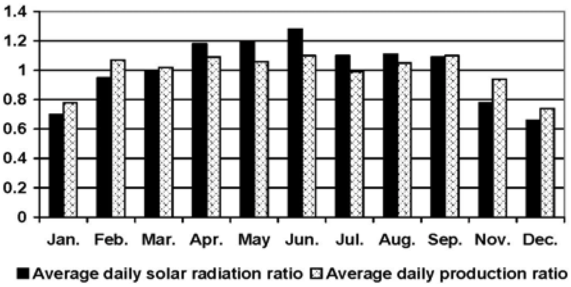

Fig. 9. Monthly average solar radiation ratio and production ratio with clean glass tubes — results of the SOLDES program.

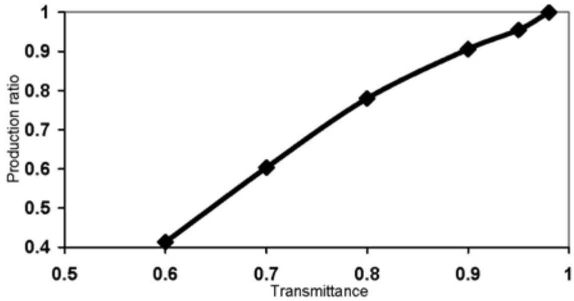

Fig. 10. Effect of collector glass tube transmittance on the annual production ratio of the solar desalination plant (production ratio = production of dusty collectors/production of clean collectors) — results of the SOLDES program.

where M_d is the annual distillate production when the collectors are dusty, $M_d^{\max}$ is the plant annual production when the collectors are absolutely clean throughout the year, and τ is the glass transmittance assumed constant throughout the year. When the collectors are clean, their transmittance was measured at 0.98 and this corresponds to a production ratio of 1.0. As dust deposits on the glass tubes, their transmittance is reduced, which results in a reduction in the solar intensity reaching the absorber plates of the collectors. This in turn results in a reduction in the amount of collected heat and a decline in plant production. If the collectors are not cleaned periodically and dust is allowed to accumulate on the glass tubes, the transmittance of the tubes can

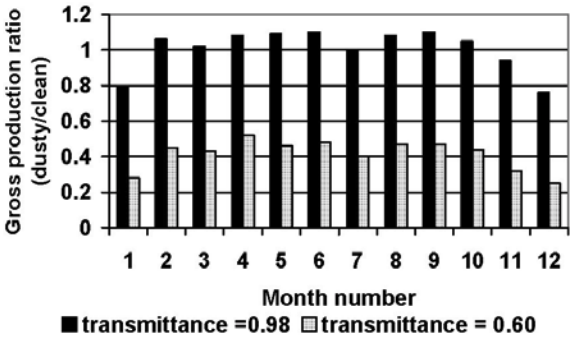

Fig. 11. Effect of collector glass tube transmittance on the monthly production ratio of the solar desalination plant (production ratio = production of dusty collectors/annual average production of clean collectors) — results of the SOLDES program.

reach as low as 0.6 and the plant production can be diminished to about 40% of maximum production.

The effect of the transmittance on the monthly average distillate production for clean glass tubes ($\tau = 0.98$) and very dusty tubes ($\tau = 0.6$) is shown in Fig. 11. This figure shows monthly values of the gross production ratio defined as the gross monthly average daily production divided by the annual average daily production with clean glass tubes. As can be seen from this figure, a very dusty collector field with a transmittance of 0.6 can result in a drastic drop in monthly plant production.

The specific water production, *SWP*, defined as the annual average plant water production per unit solar radiation impinging on a tilted surface, having a tilt angle as the collector absorber plate, liter/MJ, is an important plant performance criterion. It indicates how efficient the overall conversion process is from the solar radiation incident on the collector field to distilled water produced by the evaporator. Calculated on an annual basis, *SWP* can be expressed as:

$$SWP = \frac{\sum_{i=1}^{365} (M_d)_i}{\sum_{i=1}^{365} (I_t)_i A_c} \quad (5)$$

where M_d is the daily plant water production in L/day, I_t is the daily solar radiation on a tilted surface, MJ/day.m^2 and A_c is the total absorber area (m^2) of the solar collector field. Fig. 12 is a plot of *SWP* versus the transmittance of the glass tubes and, as expected, *SWP* increases as the plant average transmittance increases due to the fact that with higher transmittance more thermal energy is received by the accumulator which leads to more distillate production for the same amount of solar radiation. The figure shows the results of a number of computer runs for different values of collector transmittance ranging from 0.6 (very dusty) to 1 (no dust at all). For the theoretical case of "no dust" with $\tau = 1.0$, the plant could produce 2.7 L of water for one MJ of incident solar radiation. As dust deposits on the collector field with a consequent drop in transmittance, the specific water production decreases almost exponentially till it reaches 1.8 L/MJ (66.6% of "no dust" value) at a transmittance $\tau = 0.6$ (very dusty collectors).

Dust accumulation not only affects plant production but also affect its specific power consumption, SPC (kWh/m^3 distillate). This is because as the plant production decreases due to dust accumulation while the corresponding pumping power requirement decreases in the same proportion as the production rate. Fig. 13 shows how the transmittance of the glass tubes affects the plant's specific power consumption ratio. The SPC ratio is defined as the value of SPC with dusty collectors divided by the corresponding SPC of clean collectors. As can be seen, a reduction of transmittance due to dust deposition gives rise to a corresponding increase in the specific power consumption. An increase of as much as 45% in the specific power consumption can result when the transmittance drops to 0.6 (very dusty collectors) as compared with the case of clean collectors. Based on the results of many program runs, the plant specific power consumption ratio can be correlated to the transmittance by the equation:

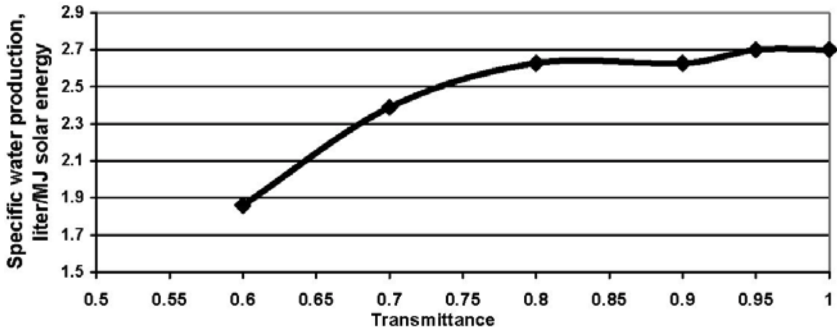

Fig. 12. Specific water production (L per MJ solar energy) for different plant transmittances — results of the SOLDES program.

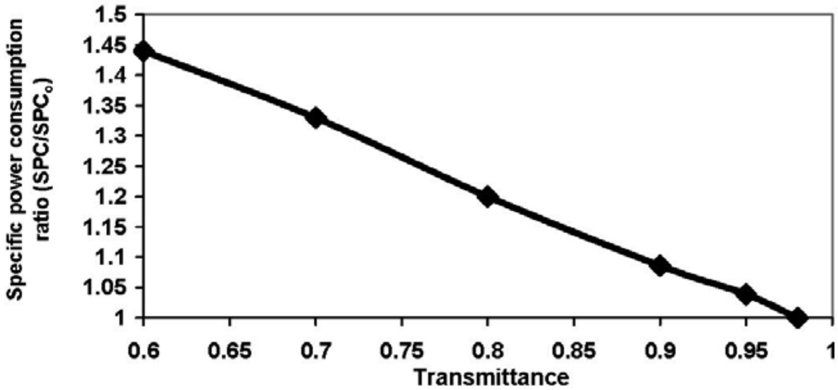

Fig. 13. Effect of collector glass transmittance on specific power consumption of Abu Dhabi solar desalination plant — results results of the SOLDES program.

$$\frac{SPC}{SPC_o} = 0.1556\tau^2 - 1.4096\tau + 2.2327 \qquad (6)$$

where SPC is the (annual average) specific power consumption for dusty collectors and SPC_o is the (annual average) specific power consumption of clean collectors. The collector glass tube transmittance τ is assumed to be maintained constant throughout the year.

Fig. 14 displays the effect of cleaning frequency on the monthly average specific power consumption, SPC, in kWh/m^3 net distillate production. For the theoretical case of no dust deposition, it can be seen that the specific power consumption assumes the minimum values since the maximum production can be achieved in this case. As the cleaning frequency increases from once per month to daily cleaning, the specific power consumption increases gradually.

To demonstrate the effect of cleaning frequency on plant production, several computer runs were made with daily, weekly and monthly cleanings carried out for one whole year. The results are shown in Fig. 15, which displays the monthly production ratio (monthly production with any cleaning frequency divided by the design capacity of evaporator) for each month of the year. It is to be noted that the daily production values shown in this figure represent the net water production which is estimated by subtracting the amount of cleaning water used from

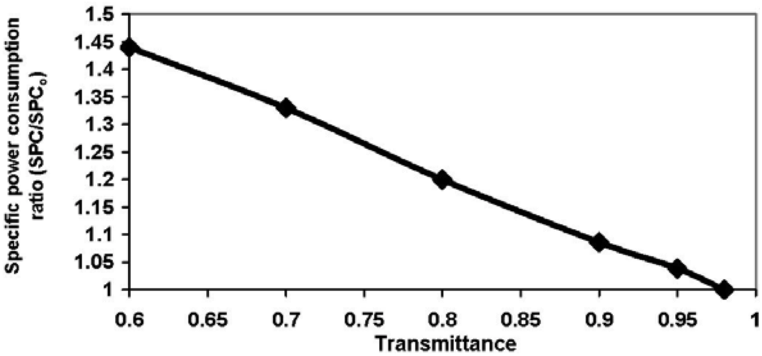

Fig. 14. Effect of collector cleaning frequency on the monthly average specific power consumption of Abu Dhabi solar desalination plant — results of the SOLDES program.

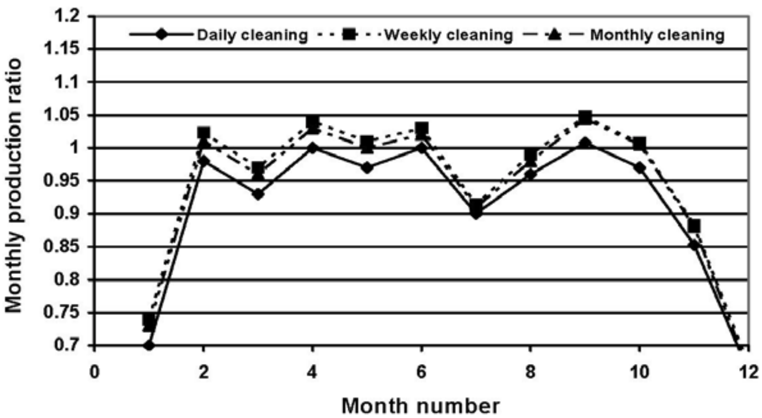

Fig. 15. Ratio of monthly average daily production ratio for different cleaning frequencies — results of the SOLDES program.

the total (gross) water production of the plant. It can be seen that the maximum monthly production ratio is achieved by a weekly cleaning regimen while a daily cleaning represents a waste of water.

The collector field cleaning frequency affects its monthly collection efficiency as shown in Fig. 16. Daily cleaning results in the highest efficiency while monthly cleaning results in the lowest efficiency. This is expected because cleaning the collectors on a daily basis insures the highest possible glass transmittance that maximizes the incident solar radiation on the absorber plant whereas monthly cleaning results in dust deposition and thus lowers transmittance.

The effect of cleaning frequency on the net plant production ratio is shown in Fig. 17. The net production ratio is defined as the ratio of net annual production for any cleaning frequency divided by the maximum annual production corresponding to the optimum cleaning frequency. Obviously, the higher the frequency of cleaning the collector field, the larger the amount of water consumed in cleaning the collector field. The annual production ratio can be correlated to the cleaning frequency by the equation:

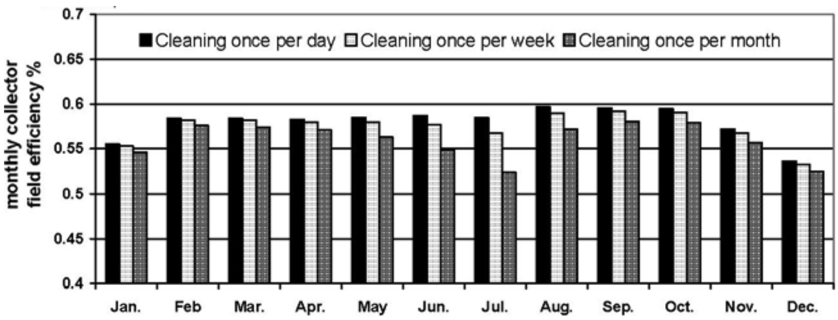

Fig. 16. Monthly collector field efficiency with different cleaning frequency — results of the SOLDES program.

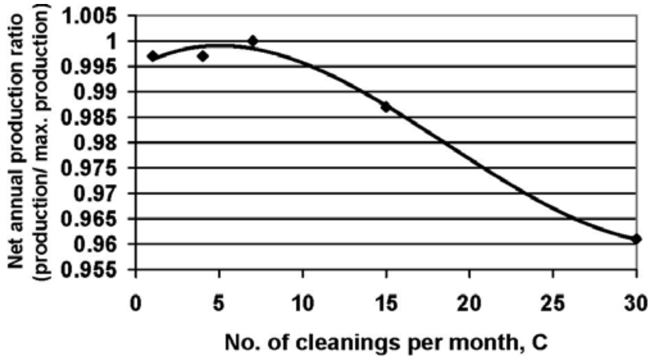

Fig. 17. Net annual water production ratio with different cleaning frequency — results of the SOLDES program.

$$\frac{M_d}{M_d^{\max}} = 4.0\left(10^{-6}\right)C^3 - 0.0002C^2 + 0.0019C + 0.9947 \quad (7)$$

where M_d is the distillate production corresponding to a cleaning frequency C (cleanings per month) and $M_d^{\max}$ is the maximum production achievable using a cleaning frequency C^* (cleanings per month). It can be seen that weekly cleaning results in the maximum distillate production.

The percentage of the monthly solar radiation incident on the collector field that is lost due to dust deposition is shown in Fig. 18 for three cleaning frequencies: daily, weekly and monthly. With daily cleaning frequency, it can be seen that the percentage of energy lost due to dust accumulation is limited to about 2% for each month of the year. With weekly and monthly cleanings, however, the percentage energy loss varies from month to month and increases substantially during summer months when sandstorms prevail.

In order to study the sensitivity of the monthly distillate production to dust deposition, a dust coefficient was introduced into the dust model of the SOLDES program. The dust coefficient is defined as the correction coefficient against the dust influence model. For a dust coefficient of 0.5, for example, the sensitivity to dust deposition is one half that specified in the program by the model. Fig. 19 shows the effect of the dust coefficient on the monthly production ratio defined as the monthly production for a given dust coefficient divided by the production for a dust coefficient of 1.0, i.e., using the dust model in the SOLDES program as is. As can be seen

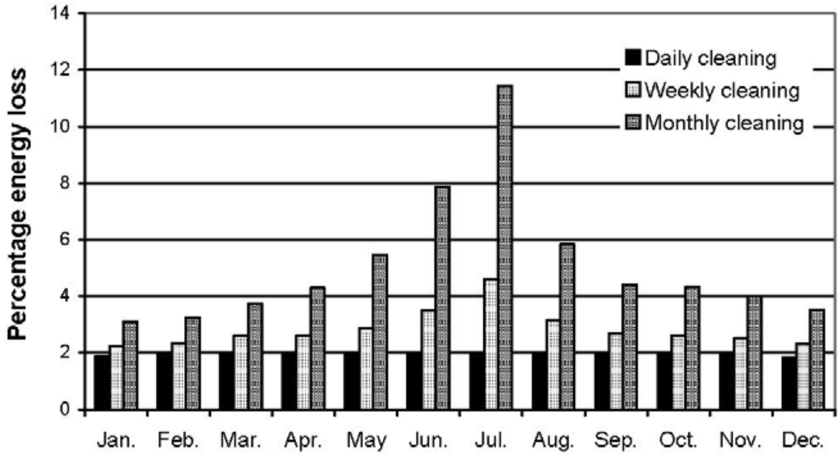

Fig. 18. Monthly solar radiation lost due to dust deposition — results of the SOLDES program.

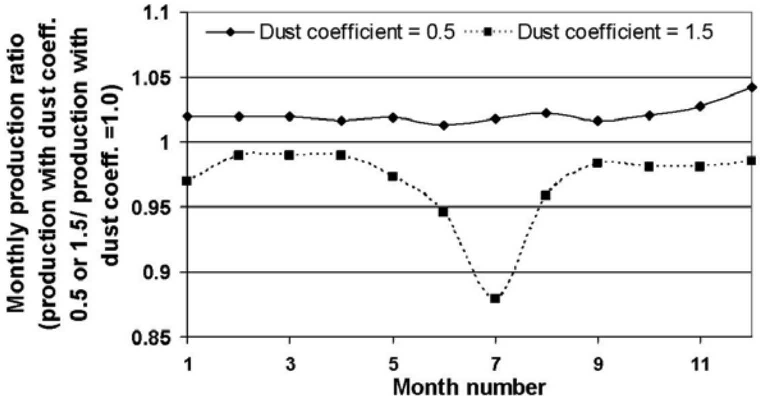

Fig. 19. Monthly production ratio for two dust coefficients — results of the SOLDES program.

from the figure, a 50% reduction in the dust model can result in a monthly increase of 2–4% in distillate production whereas a 50% increase in the dust coefficient can cause a reduction in distillate production ranging from 1–12%. The reduction is highest during the summer months where more sand deposition takes place.

6. Conclusions

The following conclusions can be drawn from this study:

- The end-of-month transmittance drop was found to vary between 2–4% during the winter months of November and December and 6–16% during the summer months (May–August).
- The transmittance of the glass tubes strongly affects plant production; for a transmittance of 0.6 (very dusty collectors) the production can drop to 40% of the clean collector production.
- The weekly cleaning frequency was found to result in the maximum water production for the location in question (Abu Dhabi).
- The specific water production (water production per MJ of incident solar energy) for the clean collector field can reach 2.7 L/MJ

solar energy but drops to 1.8 L/MJ for very dusty collectors with a transmittance of 0.6.

- The specific power consumption (electrical energy consumption per unit of net water production) increases as the transmittance of the glass tubes decreases due to dust deposition. For very dusty tubes, transmittance of 0.6, the specific power consumption increases by 45% due to the big drop in plant production.

7. Symbols

A_c	—	Total absorber area of collector field, m^2
C	—	No. of cleanings per month
C_s	—	Calibration factor
I_t	—	Daily solar radiation on a tilted surface, kcal/d m^2
m	—	Month number
M_d	—	Distilled water production, m^3/d or m^3/y
M_d^{max}	—	Plant annual production when collectors are absolutely clean throughout the year, m^3/y
M_d^{max}	—	Maximum production achievable using a cleaning frequency C^* (cleanings per month)
MED	—	Multiple effect distillation plant
N	—	Number of days after cleaning
N_m	—	Number of days in a month m
Q_A	—	Heat added to accumulator
RTD	—	Resistance temperature detector
SPC	—	Specific power consumption, kWh/m^3 distillate
SPC_o	—	Annual average specific power consumption of clean collectors, kWh/m^3 distillate
SWP	—	Specific water production, L/MJ
V_2	—	Voltage of inside sensor, V
V_1	—	Voltage of outside sensor, V

Greek

$\Delta\tau$	—	Drop in transmittance
$\Delta\tau_m$	—	Drop in transmittance during month m
τ	—	Transmittance of collector glass tube

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