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Field results in Namibia and Brazil of the new solar desalination system for decentralised drinking water production

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ABSTRACT

Areas in many rural and costal zones, particularly in developing countries, have a demand for a lower-price, low maintenance, environmentally friendly, and decentralized small-scale desalination systems. For these regions, a new thermal desalination system with heat recovery has been developed and tested in different countries. The system has two components: a desalination tower with multiple stages and a set of solar thermal collectors. Sea and ground water can be fed on the top stage of the tower, and it flows down filling the lower stages. The tower produces desalinated and decontaminated water in its 5–7 horizontal stages. The present work presents the field results of two systems tested in Brazil, and the numerical results of a design installation for Namibia. For Namibia, six systems are planned with capacity of 400–500 L/d. Seven systems use flat plate collectors and tree systems use evacuated tube collectors. In Brazil, two systems with a 35–40 L/d capacity, one with evacuated tube and the other flat plate collectors were tested. They incorporate the most recent improvements made in the components so far. The performance was evaluated by the coefficient of performance and the gain output ratio values. They were 4.78 and 2.52 for the field tests in Brazil. The simulated values for Namibia were 72 L/d for a 4.4 m² solar collector area and 1.5 m² condensation area per stage.

Keywords:Solar desalination; Decentralised drinking water production

1. Introduction

Because the demand for potable water has been increasing with the increase in population, industrialization and urbanization, it is necessary to treat salty water to produce drinkable water. It is known that only 2.5% of the water on the earth is sweet, while 97.5% is salty. The 2.5% of freshwater is distributed as: 0.001% water in the atmosphere, 1.979% in glaciers, 0.006% in rivers and lakes and 0.514% as groundwater.

Various large scale desalination plants with different techniques have been developed and installed. The installations require high investment and maintenance costs, which are not possible for less developed regions. These regions in rural and costal zones, particularly in developing countries, have a demand for a lower-price, low maintenance, environmentally friendly, and decentralized smaller-scale desalination systems.

There are different techniques to desalinate salty water. A general classification of these techniques is in thermal and membrane processes:

- Thermal processes use heat from renewable or non-

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renewable sources to evaporate pure water from salty water. These processes include: multiple stage flash desalination (MSF), multiple effect desalination (MED), humidification and de-humidification desalination (HDD), solar thermal desalination (STD), and freezing.

- Membrane processes are electrodialysis (ED) and reverse osmosis [RO].

According to [1], the multiple stage flash desalination (MSF) and the reverse osmosis (RO) processes represent 44% and 42%, respectively, of the world installed capacity. The MSF installations represent 93% of the thermal processes, and the RO installations 88% of the membrane processes.

As an alternative to the conventional desalination systems, a new solar thermal desalination system with heat recovery has been proposed and studied to help in the solution of the water shortage problem. The aim is to develop a robust and reliable multi-stage desalination (MSD) system to produce drinkable water for families and institutions where the use of large systems is too expensive to install and to maintain. The system can be filled with salty or contaminated water, inappropriate for drinking, to produce drinkable through the evaporation and condensation processes in a desalination tower. The tower maintenance is very simple and it does not use any chemical product, reducing costs and avoiding pollution to the ambient

The system has been developed and tested in different countries [2,3]. It has two components: a desalination tower with multiple stages and a set of solar thermal collectors. Sea and ground water can be fed on the top stage of the desalination tower, and naturally flows down filling the lower stages. The tower produces desalinated and decontaminated water in its 5–8 horizontal stages. The solar collectors absorb solar energy and water moves by natural convection to a storage tank in the lowest level of the tower. This water from the collectors reaches high temperatures and can partially boil, when it enters the desalination tower. The evaporated water in the storage tank rises in the tower, until it reaches the bottom surfaces of the directly above stage, which is filled with cooler, sea or ground water. On this surface, the vapor condenses and flows to the side due to this surface tilt angle (stage inclination). The condensate flows in side channels and is collected outside of the tower. When the vapor condenses, it releases its latent heat that is transferred to the stage above, and the process is repeated. The solar collectors used so far have been flat plate and evacuated tubes, but other heat sources are possible.

The system has no moving parts, it is user friendly, and it has very low maintenance costs. The disadvantages are the lower production rate, when compared to the reverse osmoses systems and its higher price, when compared to the simple distiller. For these reasons, the system is adequate for the rural and costal zones, particularly in developing countries, with a demand for decentralized smaller-scale desalination water production.

This article presents the numerical calculation of a design installation for Namibia and the field results of two systems tested in Brazil, Germany, and India. For Namibia, six systems are planned with capacity of 400–500 L/d. The systems use flat plate collector. Some systems with 35–40 L/d capacity, with evacuated tube and with flat plate collector have been tested. They incorporate the most recent improvements made in the components to increase performance and reduce installation costs.

2. Literature review

The economical use of solar energy to desalinate water is an old challenging task that has been studied by many researchers. In 2003, three papers were published in the literature reviewing the state of the art of these systems [4–6]. Most solar energy desalination stills operate at temperatures below 70°C. A comparative study on the models to estimate the thermal performance of solar desalination system was presented in [7], where the authors show that agreement is found among the models for operation below 70°C. At higher temperatures, the models do not show agreement among themselves.

More recently, a review of the theoretical models to determine the performance of these systems was recently presented in [8], where the author suggested change in a constant parameter in model presented in [9] that has been used by many researchers.

To increase the performance of a thermal desalination system, it is necessary to increase its temperature of operation. As shown in Fig. 1, there is an exponential increase in the vapor pressure of water with an increase in temperature, for evaporation temperature above 60°C. The increase in operation temperature was achieved in the present system through the use of efficient thermal collectors. The heat recovery mechanism allows the op-

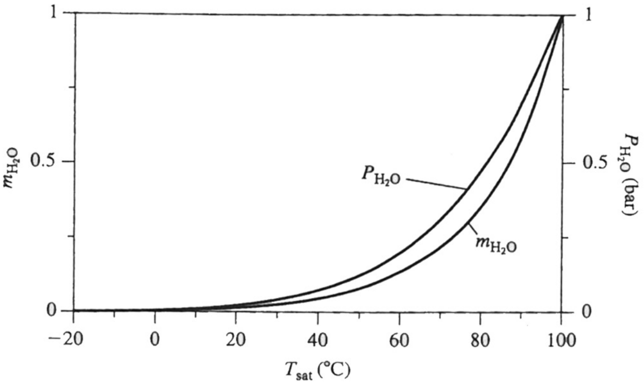

Fig. 1. Vapor pressure of water and mass concentration of water in saturated air at P = 1.013 bar. Adapted from [10].

eration of 2–3 more stages of the desalination tower at temperatures above 60°C.

3. Materials and methods

This section presents the methodology used to carry out the experimental and numerical work.

For the field tests in Brazil, one system with evacuated tube collector and five stages (Fig. 2) and one system with flat pate collectors (Fig. 3) were tested.

In the system presented in Fig. 2, except for the trays, water feeding and collecting systems, all components were manufactured in Germany and mounted in Brazil. For the measurements presented in this article, the trays were adjusted so reduce the vapor leakage from one stage to another. A top cover with side openings was added to the system to maintain the feeding water temperature near the ambient. The opening allowed the flow of wind over the feeding water.

For the system presented in Fig. 3, two flat plate collectors were manufactures with materials available in the Brazilian market, except for the absorber plate copper fins, which were selectively coated and imported from Europe. The collectors had one glass cover and one thin ultra violet resistant plastic cover. The profiles for the desalination tower were somewhat similar to the ones shown in Fig. 2, but some changes were included:

a) The geometry was slightly modified to include a pair of protuberance-hole to help align the profile one over the other
b) Collection points were included on both sides of the tower to facilitate the flow of condensate

Fig. 4 shows a schematic of the solar desalination system with indication of the measurement points. Temperature was measured with type K thermocouples located at the collector inlet and outlet, storage tank, and trays. Ambient temperature and incident global radiation on the collector tilted plane were also measured. A precision pyranometer was used.

The conductivity of the salty (in the storage tank) and the desalinated water (collected from the stages) were measured using a bench conductivity meter.

Fig. 2. System with five stages and evacuated tube collectors.

Fig. 3. System manufactured in Brazil with 6 stages and flat plate solar collectors.

4.1. Numerical model for the multi-stage desalination plant

As the energy source for the desalination system, both solar energy and waste heat can be used. The use of waste heat alone or associated with solar energy allows continuous operation.

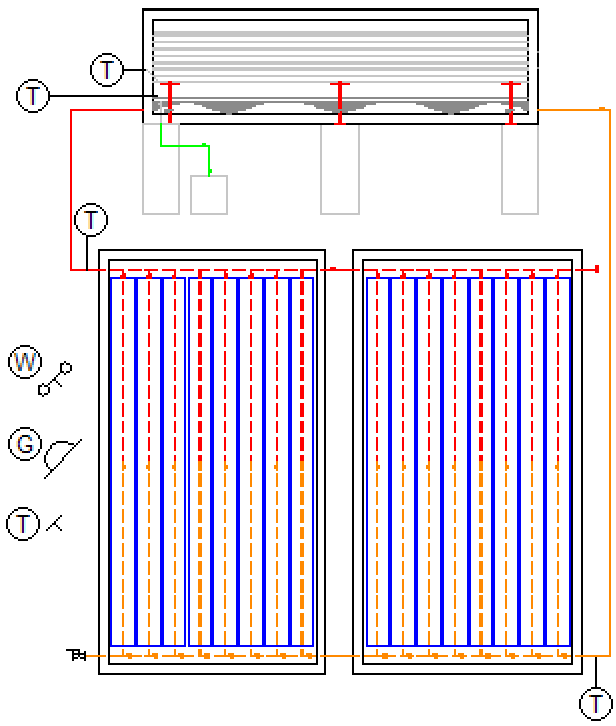

Fig. 4. Schematic drawing of the desalination system with indication of the measurement points: T – thermocouple, W – anemometer, G – pyranometer.

For the structural and thermodynamic design of the desalination system, the energy and mass fluxes from the collectors into the desalination and in the desalination tower itself have to be determined. These calculating for Namibia considered the laboratory and field tests carried out in Germany, Spain, India, and Brazil. The energy and mass balance equations are presented in this section.

4.1.1. Collector system

Fig. 5 shows the effective heat rates for a storage tank heated by solar energy. The important parameter such as collector efficiency η0 and the collector overall heat loss coefficient Ucol are generally known and the energy gain from the collector system can be written.

The expressions for the net solar heat source rate are:

$$\dot{Q}_{col}(t) = A_{col} \cdot \dot{E}(t) \cdot \eta_0 - \dot{Q}_{loss,col}(T_{col}) \tag{1}$$

or

$$\dot{Q}_{col}(t) = A_{col} \cdot \dot{E}(t) \cdot \eta_0 - \frac{U_{col} \cdot A_{col}}{\dot{E}(t)} \cdot (\overline{T}_{col} - T_{env}) \tag{2}$$

where A_{col} is the collector area, $\dot{E}(t)$ is the incident solar flux, $\dot{Q}_{loss,col}(T_{col})$ is the heat rate of the energy lost from the collector to the environment, U_{col} is the overall collector heat loss coefficient, $\overline{T}_{col}$ — the average collector temperature, and T_{env} — the environment temperature.

The heat loss rates from the storage tank can be calculated with good precision. These rates are the conduction, convection, and radiation, as well as the sensible heat flux. The coupled heat and mass transfer fluxes among the stages and the collector energy rate have uncertainties and require experimental investigation to thermodynamically characterize the system.

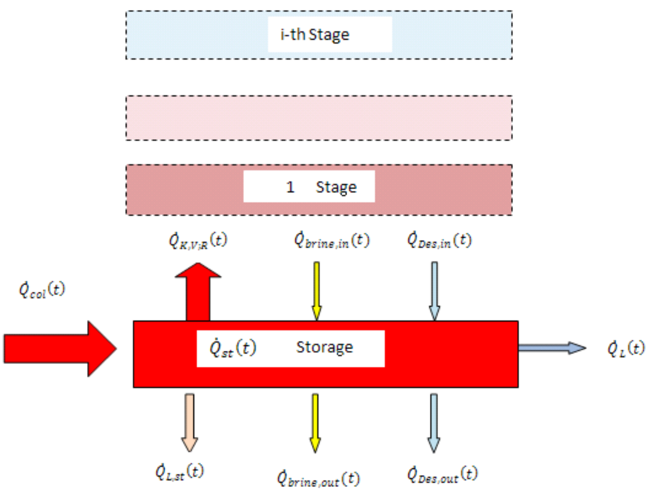

Fig. 5. Schematic drawing of the flow rates in the storage tank of the desalination system.

The heat balance in the storage tank can be written as

$$\begin{aligned}\dot{Q}_{st}(t) = \dot{Q}_{col}(t) - \dot{Q}_{K,V,R}(t) - \dot{Q}_{L,st}(t) - \dot{Q}_{L}(t) \\ - \dot{Q}_{Des}(t) - \dot{Q}_{brine}(t)\end{aligned} \tag{3}$$

The stored energy rate, $\dot{Q}_{st}(t)$, describes the heating and cooling of the masses in the storage tank and it can also be written as

$$\dot{Q}_{st}(t) = m_{st} \cdot c_p \cdot \frac{dT}{dt} \tag{4}$$

The heat rate $\dot{Q}_{K,V,R}(t)$ from the surface of the storage to the first condensation stage represent 3 parallel rates: convection, evaporation, and radiation. This rate flows upwards to heat up the salt water in the above stage as well as for the evaporation in this above stage. This process is desired and repeats itself from stage to stage in the above stages. The heat rate is strongly dependent on temperature, as presented in Eq. (7). The rate of heat lost $\dot{Q}_{L,st}(t)$ represents the side and bottom surface losses through the insulation. The terms $\dot{Q}_{brine}(t)$ and $\dot{Q}_{Des}(t)$ represent the in and out energy rates in the brine and desalinated masses. Additionally, there is the possibility of some vapor loss in the interfaces among the stages and in the tower cover. This loss is estimated by $\dot{Q}_{L}(t)$.

All stages in the desalination tower have similar energy balance, except for the first stage that lies above and receives heat from the storage tank. All other stages are heated by the stage immediately below. The energy balance in the *i*-th stage is

$$\begin{aligned}m_i \cdot c_p \cdot \frac{dT_i}{dt} = \dot{Q}_{K,V,R,i-1}(t) - \dot{Q}_{K,V,R,t}(t) - \dot{Q}_{L,st,i}(t) \\ - \dot{Q}_{L,t}(t) - \dot{Q}_{Des,i}(t) - \dot{Q}_{brine,i}(t)\end{aligned} \tag{5}$$

where

$$\begin{aligned}\dot{Q}_{K,V,R}(t) &= \dot{Q}_{Kon}(t) + \dot{Q}_{Verd}(t) + \dot{Q}_{Rad}(t) \\ &= k_{ges}(T) \cdot A_{KF} \cdot [T_{st}(t) - T_{St,1}(t)]\end{aligned} \tag{6}$$

In the equations, the subscripts *Kon*, *Verd*, and *Rad* stand for convection, evaporation and radiation. The heat transfer coefficient $k_{ges}(T)$ is determined from the experimental measurements and the condensation area, A_{KF}.

Two important parameters to characterize the performance of the desalination system are the coefficient of performance (COP) and the gain output ratio (GOR). The COP is calculated as

$$\mathrm{COP} = \frac{\sum_{i=1}^{n} m_{Des,i}}{m_{Des,1}} \tag{7}$$

where $\sum_{i=1}^{n} m_{Des,i}$ represents the total amount of desalinated water produces by all stages, and $m_{Des,1}$ the amount of desalinated water produced by the first stage. The COP is used to analyze to heat recovery processes and to optimize the efficiency of the stages. The GOR value is defined as

$$\mathrm{GOR} = \frac{\sum_{i=1}^{n} m_{Des.i} h_{fg}}{Q_{Col}} \quad (8)$$

where Q_{Col} is the energy input to the desalination tower from the solar collector, Eq. (1).

5. Results

This section presents both field and numerical results, that is, a design of an installation system for the location Akutsima, in Namibia.

5.1. Field results

For the system with evacuated tube collectors (Fig. 2), the highest temperature measured in the storage tank was 88.6°C. The temperatures in the tower trays varied from 81.1°C in the first stage to 41.6° in the fifth stage.

Fig. 6 shows the production of desalinated water on Sept. 1, 2009. The daily production was 35 L, collected at 11:30 h and at 17:10 h and the desalinated tower operated with five stages. The daily solar energy absorbed by the collector was 27.61 MJ. The GOR value for the desalination tower, considering the collector thermal efficiency was 0.50, was 2.52. This value varied from 2.5 to 3.5, depending on the daily solar radiation. With more stages (up to 8), the production rate is higher. The value is near the interval reported by [11], which was 2–3.

For this 5 stage tower operation, the first stage produced 7.33 L and the tower 35.04 L. The COP value, which relates the total mass produced by the tower with the mass produced by the first stage was 4.78. Usually, the first stage production is the highest in the tower. However, on this day, there was a leakage in the connection in the profile, where the collecting tube is inserted. Table 1 shows the production per stage for the 24-h period.

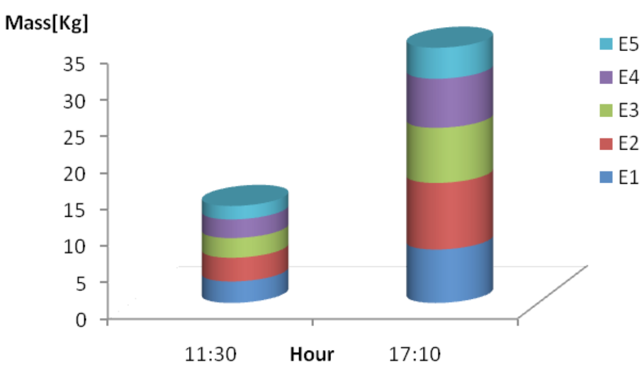

Fig. 6. Desalinated water production (for a 24-h period) at the hour of collections: 11:30 and 17:10 h. E1–E5 represent stage 1–stage 5.

Table 2 presents the total production with 3 and 5 stages mounted in the tower, in different days (different incident solar radiation). It can be noticed that the system produces desalinated water even for days with low incidence of solar radiation.

To verify the desalination process in the tower, the conductivity of the salty, feeding water in the storage tank and in the collected water from the different stages were measured. The values are shown in Table 3.

As reference values, the measured conductivity value of the city water from the local distribution varied from 250 to 300 μS/cm². The water in the storage tank was a factor of 3–4 times higher than the city water. The desalinated water was a factor of 100 times lower than the city water. These results show the effectiveness of the desalination process. The desalinated water can be adjusted to the local requirements by adding the appropriate amount of desired salts.

5.2. Simulation results

For the optimal design, knowledge of the system behavior under different solar radiation intensities is important. Only with the correct choice of the collector area, which has a strong relationship with the evaporation-condensation area and with the amount of water in the tower, the estimation of the condensation rate (system

Table 1
Total production per stage in a 24-h period on Sept. 1, 2009

	11 h 30 min	17 h 10 min	Total
Stage 1	2.950 ml	4.380 ml	7.330 ml
Stage 2	3.250 ml	5.880 ml	9.130 ml
Stage 3	2.700 ml	4.860 ml	7.560 ml
Stage 4	2.560 ml	4.170 ml	6.730 ml
Stage 5	1.840 ml	2.450 ml	4.290 ml
Total	13.300 ml	21.740 ml	35.040 ml

Table 2
Tower production on a series of days

Date	No. of stages	Production (L)	Average radiation (W/m²)
16/07/09	3	12.2	400
21/07/09	3	14.90	508
19/08/09	5	26.68	586
28/08/09	5	28.17	596
01/09/09	5	35.04	634
11/09/09	5	31.67	604
18/09/09	5	30.74	593

Table 3
Desalinated water conductivity in µS/cm²

	Date	Storage	E1	E2	E3	E4	E5
Test 1	20/08/09	906	2.79	1.79	1.44	4.31	3.28
Test 2	21/08/09	863	2.54	2.06	1.67	2.06	2.77
Test 3	24/08/09	1254	2.73	1.97	1.88	1.94	9.7

production) is possible. Based on the experimental data, a simulation program was developed. The comparison with the measured values shows good agreement and validates the use of the simulation program for different system capacities.

Fig. 7 shows the results of a one-day simulation for the location Akutsima, in Namibia, for a solar radiation of approximately 6 kWh/m². The collector area for the desalination system was 4.4 m², and the evaporation-condensation area of 1.5 m². The system consists of 7 stages with a storage tank of 60 liters. In the stages, there were 45 L of salty water. The calculated daily production for this solar radiation value was about 72 liters. The highest production rate took place at 14:00 hours and the rate was about 8 L/h (Fig. 7).

Fig. 8 shows the production rates for each stage separately for a 24-h period. At the night hours (18:00–6:00 h or 18–30 in the figure), the above stages produce more than the lower stages. This shift happens because of the accumulation of energy during the day in the tower masses (salty water and metallic parts). Fig. 9 shows the results in a column plot.

6. Comments

The results presented in this article show that the production rate of the desalination tower per m² of collector area, or the performance the heat recovery tower, is improved in comparison with the previous prototype. The improvements in the profile (flow channel geometry and material) and in the trays allowed a higher output rate of desalinated water per m² solar collector. The newest system is finished and ready for the field tests in Namibia.

Symbols

A	—	Area, m²
c	—	Specific heat capacity, kJ/kg K
COP	—	Coefficient of performance
E	—	Energy, J, energy rate, W
GOR	—	Gain output ratio
h	—	Enthalpy, kJ/kg
k	—	Heat transfer coefficient, W/m²K
m	—	Mass, kg, mass rate, kg/s
Q	—	Heat, J, heat rate, J/s

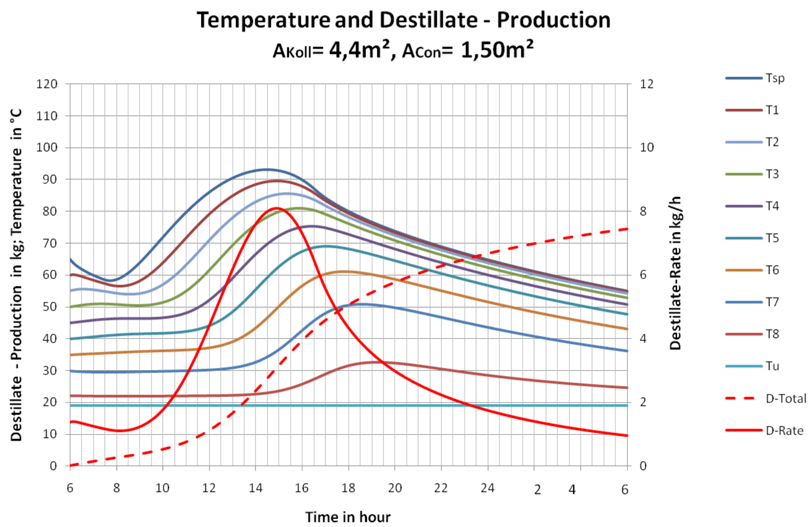

Fig. 7. Simulation results for Akutsima, Namibia – temperature profile, tower rate, and cumulative tower rate profiles.

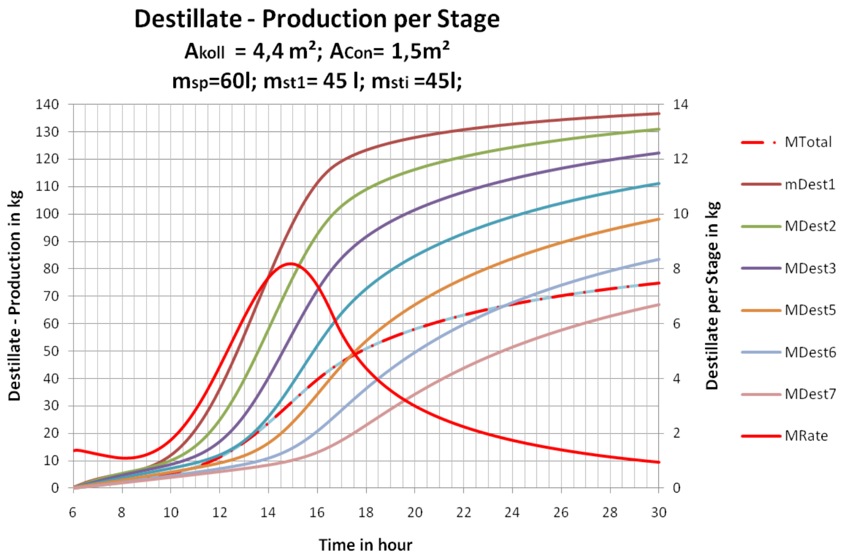

Fig. 8. Simulation results for Akutsima, Namibia – production rate profiles for the stages of the desalination tower.

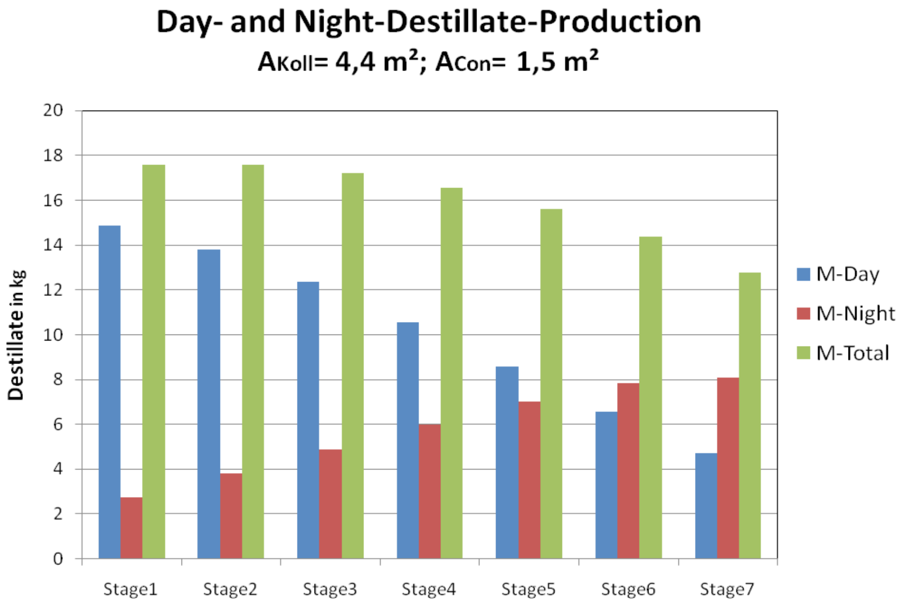

Fig. 9. Simulation results for Akutsima, Namibia – production rate profiles for the stages in column form.

t — Time, s
T — Temperature, ºC
U — Overall heat transfer coefficient, W/m²K

Greek

η — Efficiency

Subscripts

brine — Brine
col — Collector
Des — Desalination
env — Environment
f — Fluid
g — Gas
ges — Together, total
i — i-th stage
KF — Condensation area
K, Kon — Convection
L, loss — Lost
o — Optical

p — Pressure
st — Storage
R, Rad — Radiation
V, Verd — Evaporation

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