RECENT RESULTS OF THE FIELD TESTS WITH THE NEW SOLAR DESALINATION SYSTEM FOR DECENTRALIZED DRINKING WATER PRODUCTION IN NAMIBIA AND BRAZIL

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1. Introduction

It is known that only 2.5 % of the water in 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. There is an important need for potable water throughout different regions of the world and the solution to meet the increasing demand is to desalinate salty water by processing sea, ground or waste water into drinkable water.

For different desalination applications, there are different technologies to be used. Various large scale desalination plants have been developed and installed in industrialized and oil rich countries. These installations require high investment and maintenance costs, which are impossible to be met by less developed regions. Regions in rural and costal zones, particularly in developing and less developed countries, have a demand for a lower-price, low maintenance, environmentally friendly, and decentralized smaller-scale desalination systems.

A general classification of the techniques to desalinate salty water is in thermal and membrane processes: Thermal processes use heat from renewable or non-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 Electrical dialysis [ED] and Reverse Osmosis [RO]. Multiple stage flash desalination [MSF] and the reverse osmosis [RO] processes are the most commonly installed capacities.

The new solar thermal desalination system with heat recovery has been developed to contribute 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, which cannot afford the installations and maintenance costs of the MSF and RO systems. The system can be filled with salty or contaminated water, to produce drinkable water in the desalination tower. The tower maintenance is simple and it does not use any chemical product, which reduces costs and avoids polluting the ambient. The processes in the desalination tower are repeated evaporation and condensation (heat recover mechanism), which require simple maintenance work and cost.

The system has two components: a desalination tower with multiple stages and a set of solar thermal collectors. Water to be desalinated, sea or ground water, is fed on the top stage of the desalination tower, and flows down by gravity, filling the lower stages. The tower produces desalinated and decontaminated water in its 5 to 8 horizontal stages. The set of solar collectors is used as the energy source to heat up a primary water flow, which moves by natural convection to a storage tank in the lowest level of the tower. The collectors are installed in the lowest part of the system and the outlet water reaches high temperatures and can partially boil, as it enters the desalination tower. Water evaporates in the storage tank and rises in the tower, until it reaches the bottom surfaces of the directly above stage, which is filled with cooler water to be desalinated. On this surface, the vapor condenses and flows to the side due to this surface tilt angle (tray or stage inclination). The condensate flows in side channels to be collected outside of the tower. When the vapor condenses on the tray surfaces, 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 type or heat sources are possible. The system has been developed and tested in different countries (Schwarzer et al. 2009;

Silva et al. 2009). The use of waste heat alone or associated with solar energy enhances continuous operation. The desalination system has a night production due to the heat storage during the day.

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

This article presents the field results of the two latest installations, in Namibia (Akutsima, 18 °S, 15 °E) and Brazil (Fortaleza, 4 °S, 39 ºW). As part of the projects CuveWater, the German Federal Ministry of Education and Research [BMBF] between Germany and Namibia, six systems were installed with a total capacity of 500 L per day. All systems used flat plate collectors. Vacuum tube solar collectors were not used because of the possibility of hailstorms that would damage these collectors in the winter months. Field tests in other locations using vacuum tube collector showed a daily production of 20% higher than with flat plate collectors. With three collectors, the system can produce 87 L per day and with two collectors about 60 L per day. The maximum production rates were 12.5 L d^{-1} and 6 L d^{-1} for the systems, respectively. Two systems were tested in Brazil, also with flat plate collectors, 6.6 m² collector area, and 7 condensation stages. The daily production was 60-70 L per system during the raining period, with partially clouded skies and lower ambient temperatures. Higher production is expected for the dry period with clear sky.

2. Literature Review

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 by Schwarzer and Müller (2001), where the authors show that agreement is found among the models for salty water temperature below 70°C. At higher temperatures, the models do not show agreement among themselves.

The use of solar energy to desalinate water is an old theme that has been studied by many researchers. In 2003, three papers were published reviewing the state of the art of these systems (Garcia-Rodríguez, 2003; Delyannis, 2003; Tiwari et al., 2003). A review of the theoretical models to determine the performance of these systems was presented in [8], where the author suggested changes in a constant parameter in the model presented in Dunkle (1961). This latest model has been used to study systems by many researchers.

To increase the performance of a thermal desalination system, it is necessary to increase its temperature of operation. There is an exponential increase in the vapor pressure of water with an increase in temperature, for evaporation temperature above 60 °C (Kays and Crawford, 1980). This increase in operation temperature was achieved in the present work through the use of efficient thermal collectors. The heat recovery mechanism allows the operation of 2 to 3 more stages of the desalination tower at temperatures above 60 °C.

3. Materials and Methods

This section presents the procedures used to carry out the field tests and the theoretical model to determine the performance of the systems installed in Namibia and in Brazil.

The field tests took place in Namibia, where six systems were tested, and in Brazil, where two systems were tested. In all systems, flat plate collectors were installed, but in other field tests, evacuated tube collectors were used (Schwarzer et al., 2010).

Fig. 1 is a photograph of one the six systems installed in Namibia. The systems were tested with three flat plate solar collectors (6.6 m² collector area). The collectors were installed in a parallel hydraulic loop. The desalinated water from the towers was delivered by a small photovoltaic pump to a container installed above the ground for drinkable water distribution. The experience so far shows that the system is very robust and simple to operate. The salty water, pumped from a 100 m deep ground well, had very high levels of calcium carbonate and sulfates, which caused high lime and gypsum deposits in the system. Because of these deposits, the trays needed to be cleaned every 4 to 6 months. Measurements showed, however, that the production was very little affected by these deposits.

Fig. 1: Photograph of one of the six solar thermal desalination systems with heat recovery installed in Akutsima, Namibia.

Fig. 2 is a photograph of three systems installed in Brazil. The first two systems were tested with three flat plate solar collectors (6.6 m² collector area) and third one will be tested with 4.4 m² collector area. The upper water tank in this figure is used feed the system with salty water to be desalinated. The desalinated water flows out of the desalination tower and is collected in the water container shown on the side of the tower. Fig. 3 is also a photograph of the same systems, but showing the back side.

Fig. 2: Photograph of the three solar thermal desalination systems with heat recovery installed in Fortaleza, Brazil.

Fig. 3: Photograph of the back side of the three desalination systems installed in northeast Brazil.

Fig. 4 is a schematic drawing of the solar desalination system showing the measurement points. Temperature was measured with type K thermocouples located at the collector inlet and outlet, storage tank, and in the trays or stages. Ambient temperature and incident global radiation (precision pyranometer, Kipp&Konen CM21) on the collector tilted plane were also measured. The electrical conductivity of the salty (in the storage tank) and of the desalinated water (collected from the stages) were measured using a bench conductivity meter (Omega, CDB-70 Conductivity meter).

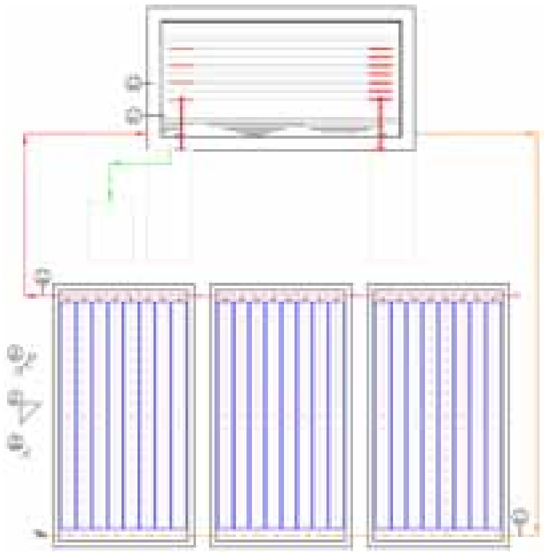

Fig. 4: Schematic drawing of the system with indication of the measurement points: T-thermocouple, and G-pyranometer.

To determine the theoretical performance of the thermal desalination system, energy and mass balance equations were written for the individual components and used in the definition of the Coefficient of Performance (COP) and the Gain Output Ratio (GOR) values.

Fig. 5 shows the schematic representation of the heat transfer rates for the storage tank heated by solar energy. The important parameters, the collector efficiency η_0 and the collector overall heat loss coefficient U_c are known from the collector technical data, and the energy gain from the collector system can be calculated. The expressions for the net solar heat rate are,

$$\dot{Q}_c(t) = A_c.\dot{E}(t).\eta_o - \dot{Q}_{l,c}(T_c) \quad \text{(eq.1)}$$

or

$$\dot{Q}_c(t) = A_c.\dot{E}(t).\eta_o - \frac{U_c\,A_c}{\dot{E}(t)}.(\overline{T}_c - T_a) \quad \text{(eq.2)}$$

where A_c is the collector area, $\dot{E}(t)$ is the incident solar flux, $\dot{Q}_{l,c}(T_c)$ is the heat rate of the energy lost from the collector to the environment, U_c is the overall collector heat loss coefficient, $\overline{T}_c$ the average collector temperature, and T_a the ambient temperature.

The heat loss rates from the storage tank can be calculated using thermodynamic properties and heat transfer correlation data. 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.

The heat balance in the storage tank can be written as,

$$\dot{Q}_s(t) = \dot{Q}_c(t) - \dot{Q}_{c,e,r}(t) - \dot{Q}_{l,s}(t) - \dot{Q}_l(t) - \dot{Q}_d(t) - \dot{Q}_b(t) \quad \text{(eq.3)}$$

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

$$\dot{Q}_s(t) = m_s.c_p.\frac{dT}{dt} \quad \text{(eq.4)}$$

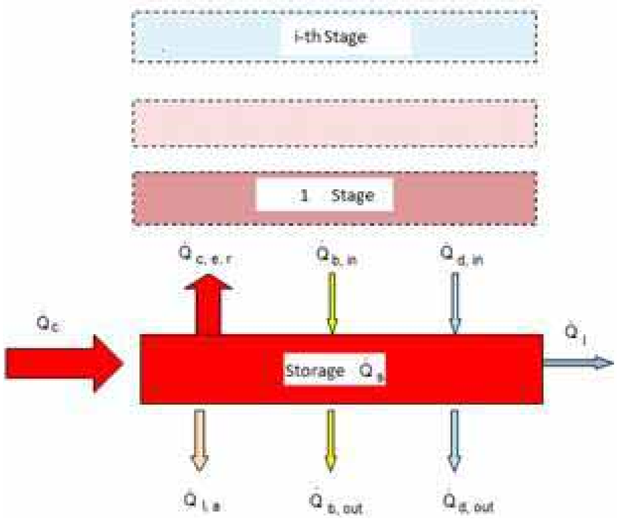

Fig. 5: Schematic drawing of the heat flow rates in the storage tank of the desalination tower.

The heat rate $\dot{Q}_{c,e,r}(t)$ from the surface of the storage to the first condensation stage represent 3 parallel rates: convection, evaporation, and radiation. These heat rates flow upwards to heat up the salt water in the above stage. The most important processes are evaporation at the water surfaces and condensation at the above tray surfaces because they are responsible for the system desalinated water production. These two processes also occur in the storage tank and in each stage. The heat rate is strongly dependent on temperature, as presented in Equation (3). The rate of heat lost $\dot{Q}_{l,s}(t)$ represents the side and bottom surface losses through the insulation. The terms $\dot{Q}_b(t)$ and $\dot{Q}_d(t)$ 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,

$$m_i\, c_p\, \frac{dT_i}{dt} = \dot{Q}_{c,e,r-1}(t) - \dot{Q}_{c,e,r,i}(t) - \dot{Q}_{l,s,i}(t) - \dot{Q}_{l,i}(t) - \dot{Q}_{d,i}(t) - \dot{Q}_{b,i}(t) \qquad \text{(eq.5)}$$

where

$$\dot{Q}_{c,e,r}(t) = \dot{Q}_c(t) + \dot{Q}_e(t) + \dot{Q}_r(t) = U_t(T)\, A_{co}\, \left[T_s(t) - T_{s,1}(t)\right] \qquad \text{(eq.6)}$$

In these equations, the subscripts c, e, and r, stand for convection, evaporation and radiation. The heat transfer coefficient $U_t(T)$ is determined from the experimental measurements and condensation area, A_{co}.

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,

$$COP = \frac{\sum_{i=1}^{n} m_{d,i}}{m_{d,1}} \qquad \text{(eq.7)}$$

where $\sum_{i=1}^{n} m_{d,i}$ represents the total amount of desalinated water produces by all stages, and $m_{d,1}$ 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,

$$GOR = \frac{\sum_{i=1}^{n} m_{d,i}\, \Delta h}{Q_c} \qquad \text{(eq.8)}$$

where Q_c is the energy input to the desalination tower from the solar collector, (eq.1).

4. Results

This section presents the field test results for the systems installed in Akutsima, Namibia and in Fortaleza, Brazil. All systems were operated with 3 solar flat plate collectors, and a total collector area of 6.4 m². In Namibia, the system was also tested with 2 collectors and the production was approximately 35% lower.

4.1. Field Results for Akutsima, Namibi.

Fig. 6 shows the temperature profile along a 24-hour period in the stages of the desalination tower (S1 to S8) and in the storage tank (Sp). The water temperature in the storage tank and in the stages 1 to 6 reached values above 60 °C. The highest temperature values were in the storage tank and reached 96 °C, as the place of installation was 1200 m above sea level.

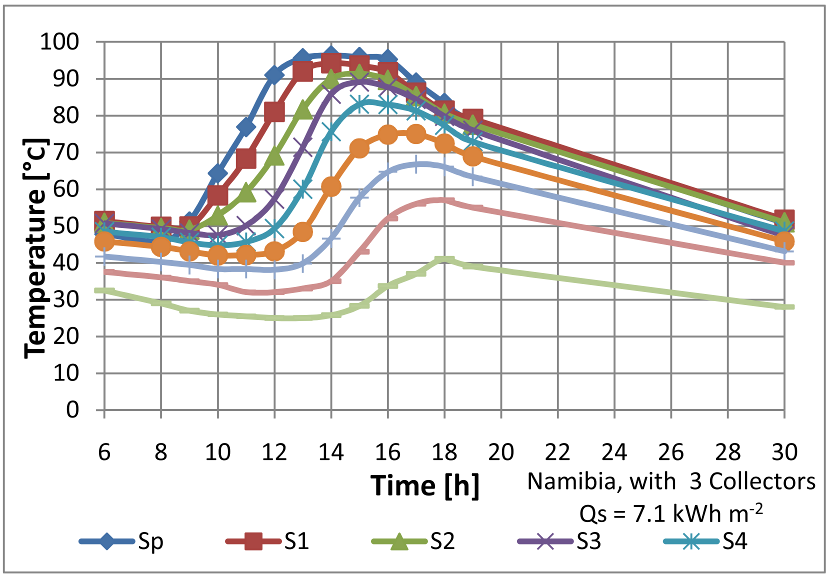

Fig. 6: Temperature profiles for a 24-hour period in the stages of the desalination tower (S1 to S8) and the storage tank (Sp).

Fig. 7 shows the plots of the total desalinated water mass and mass rate along a 24-hour period. In this period, which includes the sunshine hours and the flowing night hours, the system produced 87 L, which is an adequate amount for the daily needs of 20 people. The mass rate reached its highest value of 12 kg h^{-1} at 2:00pm. The night rates were due to the heat storage in the tower components.

The gain output ratio (GOR) value for the Namibia systems was 2.85. The COP-Value was about 5. The rate of desalinated water production as a function of the collector area was about 13 L m^{-2}.

Fig. 8 shows the plots of the system production rates as a function of the incident total radiation in a 24-hour period and for two similar systems. It is seen that the production rate shows an exponential growth for daily values higher than 5 kWh m^{-2}.

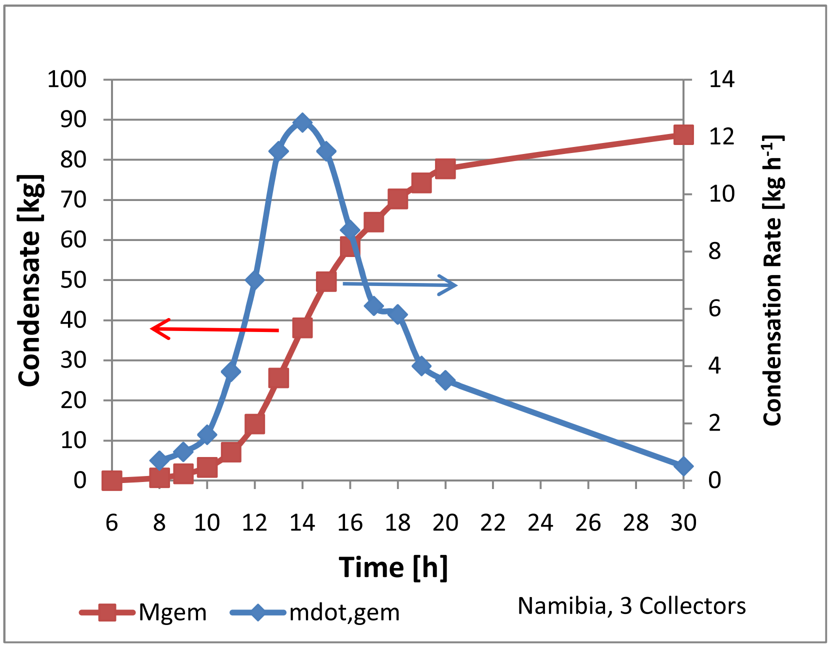

Fig. 7: Total mass rate (mdot, gem) and total mass (Mgem) profiles along a 24-hour period in a desalination system with 3 collectors and a solar radiation of 7,5 kWh m^{-2} d^{-1}.

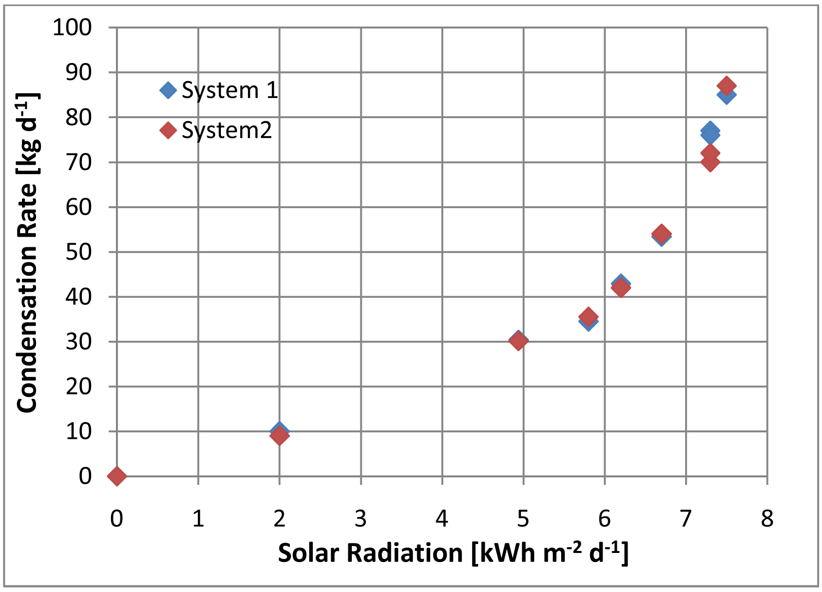

Fig. 8: Condensation rate in kg d^{-1} as function of the solar radiation for two desalination systems.

4.2. Field Results for Fortaleza, Brazil.

Fig. 9 is a similar plot to Fig. 6. It shows the temperature profile along a 24-hour period in the stages of the desalination tower (S1, S3 to S5) and in the storage tank (Sp). The water temperature values are somewhat lower than their equivalent values in Figure 6, although the incident solar radiation value was approximately the same. This result is due to lower ambient temperature values and higher wind velocity, and consequently higher thermal losses from the collector to the ambient.

The average conductivity value for the desalinated water was 1.71 µS cm^{-2} and the feed water was 510 µS cm^{-2}. As a reference values, the measured conductivity value of the city water from the local distribution varied from 250 to 300 µS cm^{-2}. The desalinated water conductivity was over 150 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.

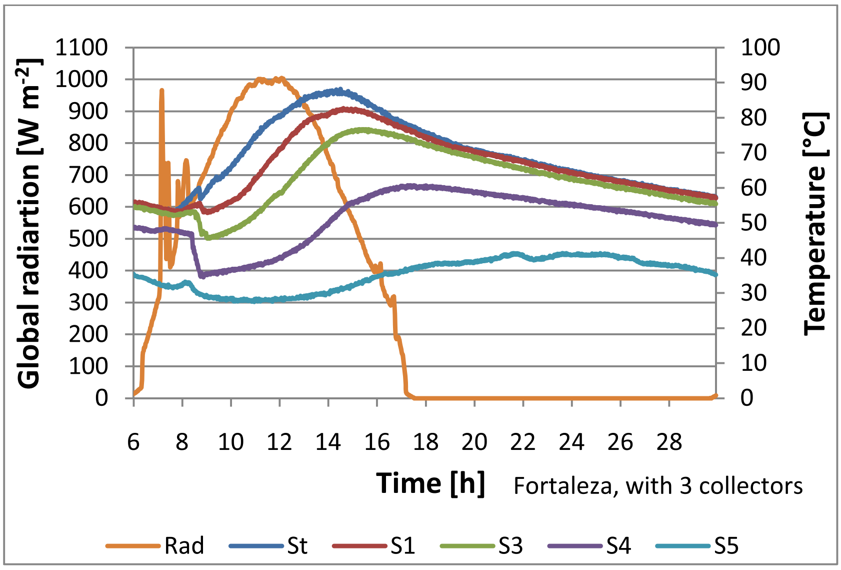

Fig. 9: Temperature profiles for a 24-hour period in the stages of the desalination tower (S1, S3 to S5) and storage tank (Sp).

5. Comments

Figs 6 to 9 show the field performance of the solar thermal desalination system with heat recovery proves its effectiveness to be used in communities. The individual units with 3 solar flat plate collectors produced 65 L to 80 L of desalinated water per day, depending on the incidence of solar radiation and ambient conditions.

The good performance of the desalination system is also due to the higher operation (evaporation-condensation) temperature in the lower stages of the desalinated tower. The heat transfer mechanism from the solar collectors to the water to be desalinated in the tower proved its effectiveness as temperatures values above 60°C were measured in 6 of the 8 stages of the desalination tower.

The excellent quality of the desalinated water was verified by the low electrical conductivity of the produced water, which was much lower, by a factor of 200, than the requirements. Water decontamination is also achieved by the system because of its high temperature operation. Laboratory results for total Coli form and fecal Coli form bacteria were presented by Schwarzer et al. (2008).

6. Acknowledgements

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Appendix: SYMBOLS AND UNITS

Table 1: Properties and materials.

Quantity	Symbol	Unit
Area	A	m^2
Specific heat	c	$J\ kg^{-1}\ K^{-1}$
Global irradiance or solar flux density	G	$W\ m^{-2}$
Enthalpy	h	$kJ\ kg^{-1}$
Mass	m	kg
Mass flow rate	$\dot{m}$	$kg\ s^{-1}$
Heat flow rate	$\dot{Q}$	W
Temperature	T	K
Overall heat transfer coefficient	U	$W\ m^{-2}\ K^{-1}$
Time	t,	s

Table 2: Greek

Quantity	Symbol	Unit
Difference	Δ	
Efficiency	η	

Table 3: Subscripts

Quantity	Symbol
Ambient	a
Brine	b
Collector, convection, condensation	c
Condensation	co
Desalination, desalinated	d
Evaporation	e
Stage	i
Losses, lost	l
Normal	n
Optical	o
Pressure	p
Radiation	r
Storage	s
Solar constant	sc
Thermal	t, th
Useful	u
Spectral	λ