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Performance Investigation of a Solar Desalination Unit Based on a Parabolic Dish Collector

M. Chahoud and S. Leila

***Abstract*--In this paper a solar desalination unit with a parabolic dish collector has been designed and characterized. Efficiency measurements of the collector provided 0.69 for the intercept efficiency and 1.9 W/m^{2}K for the first order coefficient. The effect of the feed flow rate on the distillate output flow rate has been studied. The thermal efficiency of the total distillation process including evaporation and condensation has been also determined for different feed flow rates. The maximal measured efficiency for five in series connected collectors achieved 50.2 %. The designed unit can be combined with a solar still for direct solar desalination. It can also be used as the first stage of a (MEB) or (MSF) desalination plant.**

***Keywords*-- solar desalination, parabolic collectors, Thermal solar applications.**

I. INTRODUCTION

Sustainable energy and fresh water supply are fundamental for the mankind's development all around the world. Most countries in the Middle East and North Africa suffer from the lack of fresh water. This problem increases with the continuously increase of the population. On the other hand these countries are characterized by a high solar radiation density. Consequently, the use of solar energy to desalinate brackish or sea water could play a significant role in solving the fresh water shortage problem in these countries.

Solar desalination systems can be classified into two categories, direct and indirect collection systems [1]-[2]. In the first category, the production of the distillate occurs directly in the solar collector. Whereas the systems in the second category are divided into two subsystems, one for the solar energy collection and one for the desalination. The solar energy in the indirect systems is used to generate the required heat for desalination or to provide the conventional plant with the required electricity.

The solar still is the oldest and most investigated method of the direct solar desalination systems [3]. It uses the evaporation and condensation processes of water at normal pressure to convert brackish water into fresh water. The function of the solar still is very simple; a pan of saline water is covered with a transparent plate.

The solar energy heats up the water causing evaporation within the pan and condensation on the transparent plate. The condensed water droplets slide down on the surface of the plate because of the gravitation, until they arrive the outlet of the pan. The main disadvantage of the solar still is the low thermal efficiency which is defined as the ratio of the energy utilized in vaporizing the water in the still to the solar energy incident on the glass cover [3]-[4].

TABLE I
NOMENCLATURES

Symbol	Quantity
A_c	Collector aperture (m^2)
c_w	Water heat capacity (J/kg.°C)
G_b	Direct solar radiation (W/m^2)
k_{c0}	Collector intercept efficiency
k_{c1}	First order coefficient of the collector efficiency (W/m^{2}K)
k_{c2}	second order coefficient of the collector efficiency (W/m^{2}K^2)
$\dot{m}$	Water mass flow rate (kg/sec)
$\dot{m}_{feed}$	Feed water flow rate (kg/sec)
$\dot{m}_{cond}$	condensed water flow rate (kg/sec)
$\dot{m}_{cond,\max}$	Maximal condensed water flow rate (kg/sec)
n_c	Collector efficiency
n_s	System efficiency
$\dot{Q}$	Gained energy rate or power (W)
T_a	Ambient air temperature (°C)
T_{in}	Collector inlet water temperature (°C)
T_{out}	Collector outlet water temperature (°C)
T_s	Water boiling point (°C)
y_c	Collector heat loss parameter $= (T_{in} - T_a)/G_b$ [m^{2}K/W]
λ_{evap}	Water latent heat of evaporation (J/kg)

The productivity of indirect solar desalination systems, such as multiple effect boiling (MEB) or multi stage flash (MSF) distillation, is much higher than that of the direct systems due to the latent heat recovery which occurs in several stages [5]. In each stage the condensing steam preheats the brackish feed of the next stage. The productivity increases with increased steam temperature in the first stage. Therefore the use of concentrating solar collectors, which can produce high temperature steam, is suitable for such systems.

Parabolic solar collectors can be divided into trough collectors and dish collectors [6].

Many investigations have been carried out concerning the exploitation of trough collectors in the brackish and seawater desalination [7]-[8]. Whereas parabolic dish collectors have still not obtained enough attention in this field.

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Chaouchi et. al. built a small solar desalination unit equipped with a paraboloid concentrator [9]. The absorber average temperature and the distillate flow rate as a function of solar flux have been theoretically calculated and measured. Auti presents a solar distillation system with manual tracking parabolic dish concentrator [10]. Such system could be used in rural and remote areas with no electricity access, which is needed for automatically tracking mechanism.

In this work a parabolic dish collector with automatic tracking system has been constructed and tested. The thermal efficiency of the collector is measured. In order to assess the application possibility of the collector as a part of a water desalination system, the outlet of the collector has been conducted to a separator followed by a condenser. The evaporation performance as a function of the feed flow rate has been measured in order to determine the flow rate which results in maximal produced distilled water. Additionally, the thermal efficiency of the distillation process has been determined as a function of the inlet flow rate.

Considering the need to use a large number of dishes in med- and large desalination plants, the evaporation performance of five in series connected dishes has been also investigated.

II. THE DESIGNED UNIT

The used parabolic dish has a diameter of 170 cm and a focal length of 86 cm. It is a domestic product originally manufactured for receiving satellite television signal. Square glass mirrors of 25 cm^2 surface have been stuck to the inner side of the dish using silicon paste.

The receiver of the dish consists of a square box made of 1.5 mm thick steel sheets. The side length of the box is 20 cm whereas its thickness is 1 cm. An insulating layer of 3 cm thickness, made of glass wool, covers all sides of the steel box except the side facing the reflective surface of the parabolic dish. The outside cover of the receiver is made of 0.4 mm thick aluminum plate. The heat losses of the receiver are very marginal because of its small free surface (400 cm^2) relative to the total collector surface. Therefore no transparent glass cover for the receiver is needed. The use of such cover could decrease the thermal efficiency because of the reflections at the glass surface.

This receiver design differs significantly from the well known cavity (or semi-cavity) receivers [11]-[12], where the heat transfer fluid (HTF) flows along a spiral tube covering the inside surface of a sphere. Such design is suitable for applications having high pressure HTF like solar dishes with stirling engines.

The HTF in the presented case in this paper has normal pressure. Therefore the suggested receiver design is appropriate for the intended application.

An electronic circuit with sun light sensors has been installed to the collector. This circuit guarantees together with two linear actuators the automatically tracking of the sun in the east-west direction as well as in the north-south direction.

Simple manufacturing steps and low cost locally available materials were chosen in the above described designing process. These measures could reduce the efficiency of the collector; however they are very helpful in the introducing such techniques in countries and areas with low technical development.

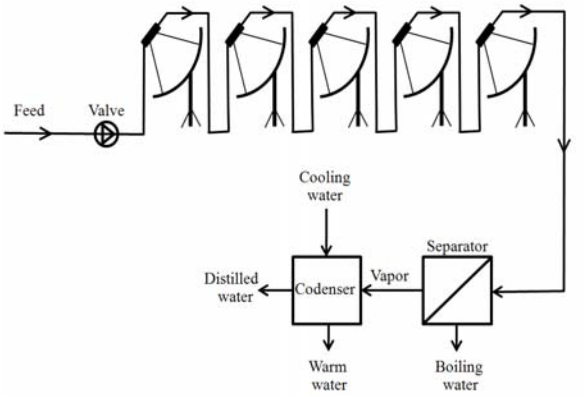

Fig. 1. The experimental setup with 5 in series connected dishes.

The first experimental setup aims to determine the thermal efficiency of the parabolic collector n_c under standard conditions as a function of the collector heat loss parameter y_c. Thus, an isolated water tank is connected to the inlet and outlet of the receiver using flexible thermally isolated plastic tubes. A water pump with nominally 2 kg/min flow rate circulates the water between the receiver and the water tank. The ambient temperature (T_a) as well as the temperature at the inlet of the receiver (T_{in}) and at its outlet (T_{out}) are measured hourly at a sunny cloudless day. Additionally, the direct solar radiation (G_b) and the water flow rate ($\dot{m}$) are measured hourly.

The determination of the evaporation performance as a function of the feed flow rate is the goal of the second setup. The inlet of the receiver is connected to the water feed, whereas the outlet is connected to a separator. The vapor outlet of the separator is connected to a condenser. The condensed water flow rate $\dot{m}_{cond}$, resulting from the condenser is measured for different values of the water feed flow rate $\dot{m}_{feed}$. Simultaneously, the direct solar radiation intensity G_b, the water feed temperature T_{in} and the temperature of the water outgoing from the receiver T_{out} are measured.

Five dish collectors have been connected in series as shown in Fig. 1 in the third experimental configuration. The same quantities have been measured as in the last experiment. The purpose of this test is the investigation of the total evaporation behavior of the collector group. This testing is important should this type of collectors be used in large desalination plants, where some tens of dish collectors could be connected in series in one array.

Heat recovery measures from the separator and the condenser are not undertaken as the purpose of this study is the testing of the evaporation performance of the collector system. Such kind of measurements will be performed in future activities.

III. RESULTS AND DISCUSSION

A. COLLECTOR THERMAL EFFICIENCY

The dependence of the thermal efficiency of a solar concentrating collector on the design and operational factors is given by the following equation [6]:

$$n_c = k_{c0} - k_{c1} \cdot y_c - k_{c2} \cdot G_b \cdot y_c^2 \qquad (1)$$

Where y_c is defined as the difference between the water inlet temperature and ambient temperature divided by the direct solar radiation intensity.

Usually the second order term is neglected (k_{c2}=0), so that (1) becomes of first order:

$$n_c = k_{c0} - k_{c1} \cdot y_c \qquad (2)$$

The tested solar collector utilizes only the direct solar radiation because of its parabolic shape. Therefore only the direct solar power is taken into account for the determination of the thermal efficiency. This disadvantage of the parabolic collectors in contrast to non-focusing collectors, which utilize direct and indirect solar radiation, is compensated through the continuous tracking of the sun.

The gained energy rate can be calculated using the following well known formula:

$$\dot{Q} = \dot{m} \cdot c_w \cdot (T_{out} - T_{in}) \qquad (3)$$

Given the direct radiation rate by $\dot{Q}_{rad} = A_c \cdot G_b$, the efficiency can be written as follows:

$$n_c = \frac{\dot{Q}}{A_c \cdot G_b} = k_{c0} - k_{c1} \cdot y_c \qquad (4)$$

T_a, T_{in}, T_{out}, $\dot{m}$ and G_b have been measured hourly at a sunny cloudless day. Using (3) and (4) we obtain one point (y_c, n_c) for each measuring set (T_a, T_{in}, T_{out}, $\dot{m}$, G_b). Fitting of formula (4) to the measuring points (y_c, n_c) results in 0.69 for the value of k_{c0} and 1.9 W/m^{2}K for the value of k_{c1}.

The value of k_{c0} can be improved if the reflectivity of the mirrors and the absorbance of the receiver surface are increased. Whereas the improving of the receiver thermal isolation will result in decreasing the first order coefficient k_{c1} which is a measure for the heat loses from the receiver.

B. EVAPORATION PERFORMANCE

The evaporation performance of the designed distillation unit depends strongly on the inlet water flow rate $\dot{m}_{feed}$. Therefore the working range of the system can be divided into two sub ranges. We assume that $\dot{m}_{feed,1}$ represents the flow rate which just leads to evaporate the whole feed water i.e. no boiling water flows out from the separator and the vapor temperature equals the boiling temperature T_s. If the feed flow rate is lower than $\dot{m}_{feed,1}$, then the absorbed energy in the receiver is greater than the required energy to evaporate the whole quantity of the incoming water to the receiver. The vapor temperature in this range is higher than the boiling temperature, i. e. vapor is superheated.

The second sub range is characterized through feed flow rates greater than $\dot{m}_{feed,1}$. We have in this range two phase stream outgoing from the receiver. The absorbed solar energy is insufficient to evaporate the entire incoming water, i. e. water is subcooled.

Fig. 2 shows the measured dependence of the condensed water flow rate $\dot{m}_{cond}$ on the feed flow rate $\dot{m}_{feed}$ for two different levels of the direct solar radiation G_b. The straight line, which indicates the equality between $\dot{m}_{feed}$ and $\dot{m}_{cond}$, is also depicted. The cross points a and b represent the best working points for the two values of G_b. Working at these points leads to the maximal achievable condensed water flow rate $\dot{m}_{cond,\max}$.

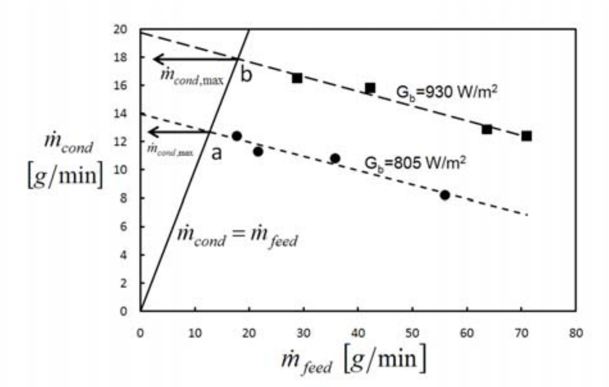

Fig. 2. The condensed flow rate as a function of the feed flow rate for two solar radiation intensities.

The thermal efficiency n_s of the entire unit including the collector, the separator and the condenser has been calculated for different feed flow rates using the following formula:

$$n_s = \frac{\dot{Q}}{A_c \cdot G_b} \qquad (5)$$

The measured temperature of the outgoing water from the receiver equals the boiling temperature T_s for all values of the feed flow rate $\dot{m}_{feed}$. Therefore, the gained power $\dot{Q}$ can be considered as the heating rate from T_{in} to the boiling point T_s of the feed flow and the evaporation energy of the condensed flow:

$$\dot{Q} = \dot{m}_{feed} \cdot c_w \cdot (T_s - T_{in}) + \lambda_{evap} \cdot \dot{m}_{cond} \qquad (6)$$

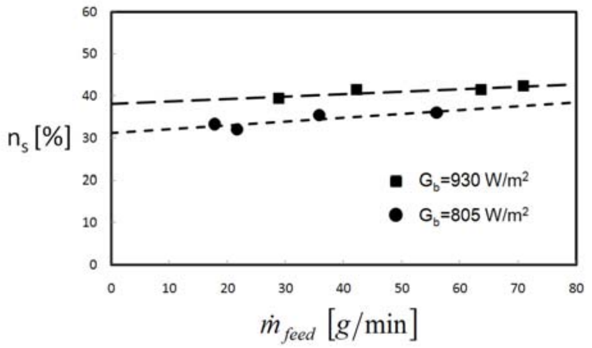

Fig. 3. The system thermal efficiency as a function of the feed flow rate for two solar radiation intensities.

Fig. 3 shows the measured thermal efficiency of the unit as a function of the feed flow rate for two different values of G_b. The efficiency increases with increasing the flow rate. This behavior is well expected due to improved heat transfer from the receiver with increased water flow rate.

Formula (6) can be simplified for the maximal achievable condensed flow rate $\dot{m}_{cond,\max}$ (points a and b) if we take into account the equality between $\dot{m}_{feed}$ and $\dot{m}_{cond}$.

$$\dot{Q} = \dot{m}_{cond,\max} \cdot [c_w \cdot (T_s - T_{in}) + \lambda_{evap}] \qquad (7)$$

The thermal efficiency n_s for point a achieves a value of 32% , whereas it is 39.5% for point b.

Five collectors have been connected in series (Fig. 1) in order to assess the application possibility of the dish system in mid- and large scale desalination plants. The effect of the feed flow rate on the condensed flow rate as well as on the thermal efficiency of the dish array has been investigated.

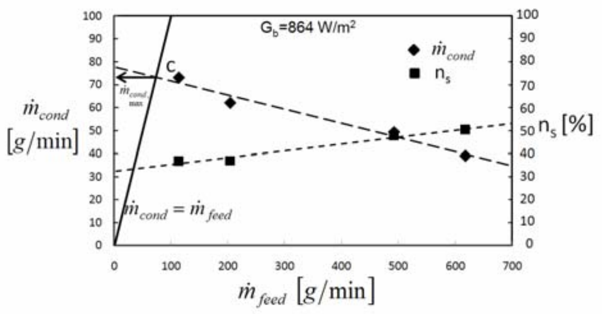

Fig. 4. The condensed flow rate and the thermal efficiency as a function of the feed flow rate for a dish array containing 5 dishes.

The left ordinate in Fig. 4 shows the condensed flow rate $\dot{m}_{cond}$, whereas the right one shows the efficiency n_s as a function of the feed flow rate $\dot{m}_{feed}$. The equality line between $\dot{m}_{cond}$ and $\dot{m}_{feed}$ is also drawn in Fig. 4. The measured direct solar radiation G_b is 864 W/m^2. In comparison to Fig. 2 and 3, similar behavior of $\dot{m}_{cond}$ and n_s can be observed. The condensed flow rate increases with decreasing of the feed flow rate. The maximal achievable condensed flow rate $\dot{m}_{cond,\max}$ (point C in fig. 4) is about 73 g/min. The thermal efficiency increases with increasing the feed flow rate. The maximal measured efficiency is 50.2 %. However, the condensed flow rate for this point is 38.9 g/min. This value is much lower than the maximal achievable value $\dot{m}_{cond,\max}$. Therefore the choice of the working point should be adopted according to the specific application, which is determined through the following stages or equipments.

The presented parabolic solar collector can be combined with a solar still. In this case the parabolic collector preheats the still feed water to temperatures close to the boiling point, whereas the preheated water evaporates in the solar still. In such combination the thermal efficiency n_s of the parabolic collector is higher than the thermal efficiency of the point with the maximal condensed water flow rate $\dot{m}_{cond,\max}$ (a and b in fig. 2). Using the preheated feed water for solar still desalination improves the efficiency of the still drastically. This is reported in [13] for single stage and for multi-stage desalination. Therefore the combination of the parabolic collector and the solar still could result in outstanding performance.

The productivity of multiple effect boiling systems (MEB) or multi stage flash systems (MSF) increases with increased steam temperature in the first stage. Therefore it is suitable to use parabolic dish collectors in the first stage of such systems. In this case the working point should be chosen in the range $\dot{m}_{feed} < \dot{m}_{cond,\max}$. In this range the steam temperature increases with decreasing of the feed flow rate.

IV. CONCLUSION

The thermal efficiency of the designed collector has been tested. The intercept efficiency k_{c0} achieved the value 0.69, whereas the value of the first order coefficient k_{c1} was 1.9 W/m^{2}K.

The influence of the feed flow rate on the evaporation performance of the collector has been also tested. The condensed water flow rate increases with decreasing of the feed flow rate in the testing range. The maximal achievable condensed flow rate is determined for two different solar radiation intensities. The thermal efficiency of the evaporation unit including the collector, the separator and the condenser has been measured for different feed flow rates. It is found that the efficiency increases with increasing the feed flow rate.

The possibility of connecting several collectors in one array is presented. This is important if the dish collectors should be used as the first stage in MEB or MSF desalination plants. The evaporation performance of five in series connected dishes is investigated. The thermal efficiency increases with increasing the feed flow rate. In contrary, the condensed flow rate decreases as the feed flow rate increases.

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