Desalination 337 (2014) 60–66

Contents lists available at ScienceDirect

Desalination

journal homepage: www.elsevier.com/locate/desal

Numerical investigation of a simple solar still coupled to a compression heat pump

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HIGHLIGHTS

- We model a solar still coupled with a compression heat pump.
- The model was validated with experimental data previously obtained.
- The productivity of the still is 75% higher compared to conventional still.
- The productivity of the still is sensitive to some parameters.

ARTICLE INFO

Article history:
Received 12 March 2013
Received in revised form 9 January 2014
Accepted 15 January 2014
Available online 6 February 2014

Keywords:
Solar still
Compression heat pump
Mathematical model
Performance

ABSTRACT

The present paper undertakes a theoretical study of a simple solar still coupled to a compression heat pump. In fact, a mathematical model has been developed using mass and heat balance. It is through a comparison with the performance of the conventional solar still under the same weather conditions that the performance of the proposed solar still is evaluated. The simulation results showed that the efficiency of the solar still with compression heat pump is 75% higher than that of the conventional solar still. The influence of some design and operational parameters were also studied. The predicted values were found to agree well with the existing experimental data.

1. Introduction

It is well-known that fresh water is crucial to life, industrial development, economic growth, natural resource preservation and social well-being. Due to economic and social development, the demand for fresh water resources continues to grow. It is expected that by 2025, more than 60% of the world's population will have water shortage [1].

Saline water desalination is one of the viable approaches to mitigating the lack of fresh water. Indeed, solar desalination systems are currently used throughout the world and have seen remarkable development over the past years. Solar stills can partially meet man's need for drinking water with free energy, simple and cheap technology and a clean environment, particularly in remote areas, where solar energy is available abundantly but with bad water quality. A simple solar still consisting of a water basin and single glass cover is the first proposed design of solar still that is easy to build and has virtually no operating cost but its problem is the low productivity. This problem has motivated scientists to investigate various methods to improve the still's productivity. Among the methods used are those concerned with cooling the glass cover. As the water vapor condenses on the glass cover, its latent heat is released to the glass cover, which increases the cover temperature and lowers the temperature difference between the water in the basin and the glass cover, thus reducing the driving force for water evaporation. Other approaches have been used to increase basin water temperature, evaporation and condensation surface areas.

Abu-Arabi et al. [2] have proposed a mathematical model of a regenerative solar still and shown that the regenerative still gives more than 70% higher productivity in comparison with a conventional still. A wick basin type solar still was designed by Shukla et al. [3], who have proven that the productivity of the wick basin is 29.6% higher than that of the conventional still. As for Fatani et al. [4], they presented an experimental and analytical study of a solar still assisted by a passively cooled condenser. Besides, Velmurugan et al. [5] used fins and sponge cubes to improve the evaporative rate. Double glass cover cooling was used and studied by Zurigat et al. [6], who found a 34% increase in productivity compared with the conventional solar distiller. Regarding A1-Hinai et al. [7], they carried out a parametric investigation of single-effect and double-effect solar stills that were mathematically modeled and simulated under the weather conditions of Muscat, Oman. They reported that under optimized conditions, the average daily productivity could reach 4.15 kg/m^2/day and 6.0 kg/

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http://dx.doi.org/10.1016/j.desal.2014.01.010

m^2/day for the single and double-effect stills, respectively. They found that the unit cost saves 15.7% when using a double effect solar still. Madhlopa and Johnstone [8] studied theoretically a single-slope passive solar still with a separate condenser. They also discovered that the productivity of the still is 62% higher than that of the conventional type.

The desalination system that utilizes heat pump as energy source is commonly applied. Experimental work on heat pump assisted water purification has been carried out in Mexico since 1981 [9]. Siqueiros and Holland studied the performance and the cost of a vapor compression heat pump assisted water purification plant. A thermodynamic analysis presented by Slesarenko [10] indicates that the desalination plants integrated with compression heat pumps could be considered to produce distillate from seawater. These systems can maintain water supply of high quality for small fixed and mobile consumers of fresh water. Hidouri et al. [11] presented an experimental study of a solar still connected to a heat pump. They found that the daily output increased from 2 l/m^2 for a simple solar still to 12 l/m^2 for the new solar still.

The present paper suggests another configuration of solar still, which can enhance its productivity without losing its simplicity in design and operation. The proposed solar still was coupled to a compression heat pump in order to increase the temperature in the basin and the condensation surface area. The objective of this work is to simulate the performance of the solar still. To do so, a validation of the elaborated model was first carried out. Then, the performance of this solar still was evaluated through a comparison with the performance of a conventional solar still. Finally, the influence of many parameters was studied to define the optimal operation conditions of the solar distiller.

2. System description

The simplified scheme of the solar still coupled to a compression heat pump is shown in Fig. 1. The system consists mainly of a basin that accommodates brackish water, a glass cover and a compression heat pump. The compression heat pump is made up of a condenser immersed in the water basin, evaporator located below the upper region of the glass cover, compressor and expander. The condenser will contribute to heat basin water, and thus its evaporation, during day time and especially during periods of low irradiation by the refrigerant (R134a) flowing through the heat pump. On the other hand, the evaporator will condense a large part of the water vapor. The water in the basin is heated by the incident solar radiation transmitted through the transparent glass cover and the condenser. Some of the water will evaporate and condense under the glass and the evaporator. Then, the condensate will be recovered by two collectors.

3. Still thermal models

A mathematical model was developed to simulate the performance of this solar still. It was assumed that:

- The water temperature gradient through the water is negligible,
- The system is vapor tight and the side losses are negligible,
- The heat conduction within the still is negligible.

The solar still heat and mass balance equations for the system components are as follow:Balance energy for the glass cover

$$m_g \cdot C_g \cdot \frac{dT_g}{dt} = \left(1-\rho_g\right) \cdot \alpha_g \cdot G_H + \left(q_{ev,w-g} + q_{r,w-g} + q_{c,w-g}\right) - q_{r,g-a} - q_{c,g-a}$$

Balance energy for the evaporator

$$m_e \cdot C_e \cdot \frac{dT_e}{dt} = q_{c,w-e} + q_{ev,w-e} - q_{ev,f}$$

Balance energy for the water

$$m_w \cdot C_w \cdot \frac{dT_w}{dt} = \left(1-\rho_g\right) \cdot \left(1-\alpha_g\right) \cdot \alpha_w \cdot G_H - \left(q_{ev,w-g} + q_{r,w-g} + q_{c,w-g}\right) \cdot \frac{A_g}{A_w} + q_{c,b-w} + \frac{W}{A_w}$$

Balance energy for the absorber

$$m_b \cdot C_b \cdot \frac{dT_b}{dt} = \left(1-\rho_g\right) \cdot \left(1-\alpha_g\right) \cdot (1-\alpha_w) \cdot \alpha_{b.} G_H - q_{c,b-w} - q_{loss}$$

Condensation rate

$$\frac{dm_c}{dt} = \frac{q_{ev,w}}{H_w} = \frac{A_w \cdot q_{ev,w-g} + A_e \cdot q_{ev,w-e}}{A_w \cdot H_w}$$

The expressions for each term in the above equations are:

– The radiation heat transfer between water and glass cover is given by [6,12]:

$$q_{r,w-g} = 0.9 \cdot \sigma\left(T_w^4 - T_g^4\right)$$

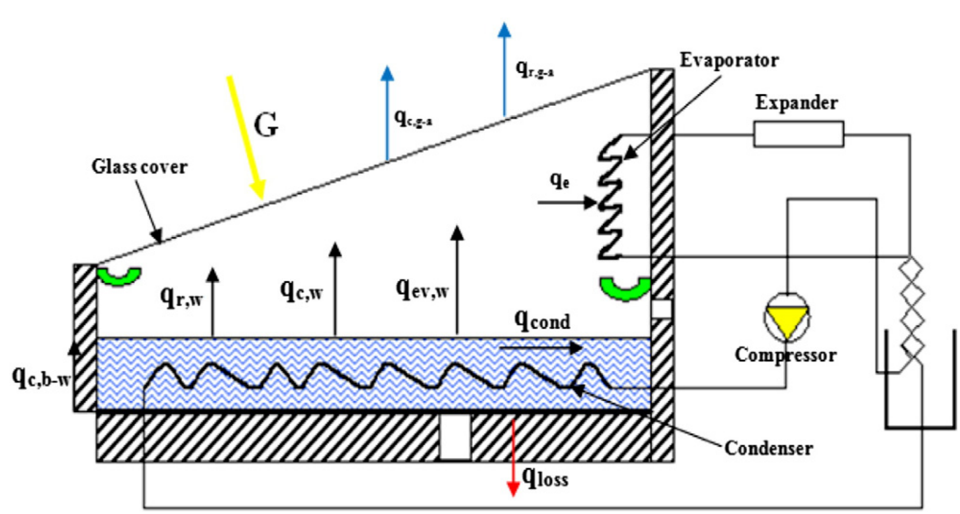

Fig. 1. Energy balance of the solar still coupled to a compression heat pump.