Desalination 409 (2017) 80–95

Contents lists available at ScienceDirect

Desalination

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

Study of heat and mass transfer phenomena and entropy rate of humid air inside a passive solar still

Yemna Sarray, Nejib Hidouri *, Ali Mchirgui, Ammar Ben Brahim

Gabès University, National School of Engineers, Applied Thermodynamics Unit, Omar Ibn El Khattab Street, 6029 Gabès, Tunisia

HIGHLIGHTS

- Heat transfer phenomena
- Mass transfer phenomena
- Uncertainty analysis
- Entropy rates of humid air (dry air, water vapor, and humid air)

ARTICLE INFO

Article history:
Received 17 May 2016
Received in revised form 4 January 2017
Accepted 10 January 2017

Keywords:
Solar still
Humid air
Entropy rate
Heat transfer
Mass transfer

ABSTRACT

The paper reports a comprehensive study of heat transfer, mass transfer, and entropy rate of humid air for a single solar still, concerning a typical summer day in a south east region of Tunisia. Transient humid air characteristics such as: partial pressures of components, temperature, humidity ratio, molecular diffusivity, and thermal diffusivity are determined and investigated. Entropy rate equation is derived and studied. Influences of humid air temperature and pressure on heat and mass transfer and on entropy rate are studied. It was found that the increase of water vapor partial pressure and humid air temperature are the best conditions for improving solar still productivity. Humid air can be regarded as a heat engine that generates kinetic energy by transporting energy from heated water surface to inner glass cover surface. Entropy rate of humid air largely depends on dry air entropy rate. The latter presents negative sign, meaning dissipation of convection heat transfer between evaporating and condensing surfaces during circulation. Inversely, entropy rate of water vapor has a positive sign, meaning that it receives energy during phase change by evaporation and transport by humid air from saline water surface towards the inner glass cover surface.

Contents

* Corresponding author.
E-mail address: n_hidouri@yahoo.com (N. Hidouri).

http://dx.doi.org/10.1016/j.desal.2017.01.009

1. Introduction

About 97% of the water in the world is in the oceans, 2% of the water is stored as ice in polar regions, and only 1% is fresh water that is available for plants, animals, and human life requirements [1]. Facing to the shortage of fresh water, the use of solar distillation can be considered as a promising option to convert saline or brackish water into fresh water, by simply using solar energy, which is freely and abundantly available in the earth. The required energy to evaporate water at atmospheric pressure, that is the latent heat of vaporization, is about 2260 kJ/kg. It is an important quantity of energy, which needs the use of considerable quantities of fossil fuel, with dramatic environmental impacts. For this reason, many researches have been focused on the use of solar energy with different designs. For a single solar still, the basin plate is usually painted with black color to absorb maximum solar heat, and the treated water (saline or brackish) is kept in the basin plate, and it is exposed to solar radiation. Water is then evaporated and it condenses as it comes in contact with the basin cover. The performance of solar stills (i.e. the quantity of produced fresh water) is the subject of many works. It was established that there are three major conditions that affect the distillation productivity [2]:

- Ambient conditions, such as: ambient temperature, wind velocity, dust, and cloud cover.
- Operating conditions, such as: water depth, various dyes, salt concentration, and inlet temperature of water.
- Design parameters, such as: different passive/active designs of solar stills, slope of the top cover, materials selections, storing materials, use of reflectors, insulation, gap distance, cover thickness, and sun tracking systems.

The solar still performance could not be improved or predicted by the uncontrollable parameters, like solar radiation, ambient temperature, and wind speed. However, some other controllable factors such as: the water depth, the glass cover inclination angle, the fabrication materials, the inlet temperature of water in the basin, the sun tracking system, the glass cover thickness, and the use of the basin plate finned surface, affect the solar still performance and could be modified for improving the water productivity [3–7]. For instance, a theoretical and numerical analysis concerning the productivity of a single solar still was performed [8]. Results show that there is an optimum solar still length, for which the hourly yield is maximum. Optimum length and maximum productivity are: $L_{opt} = 0.56$ m, and $\dot{m}_d = 0.76$ kg/h·m^2, respectively. Further, a relationship between the water productivity and the humid air temperature was established. It is given by:

$$\dot{m}_d = \frac{h^c_{w-g}}{h_{fg}}\left(c_1 T^3_{ha} + c_2 T^3_{ha} + c_3 T^3_{ha} + c_4\right)(T_w - T_{gi}) \quad (1)$$

c_1, c_2, c_3, and c_4 are constants.

Solar energy efficiency evaluation is of great fundamental and practical importance, since it shows how the water productivity can be improved via the controllable parameters. It was first done by analysis of the first law of thermodynamics, where the quantitative aspect of the transferred energy is identified. Recently, many researches focus on the second law analysis via the exergy analysis. The knowledge of the exergy analysis can be used for optimum design of a solar still, in order to get maximum productivity. Torchia-Nunez et al. [9] performed an exergy analysis for a passive solar still. Results show that for the same exergy input, a collector, brine, and solar still, have exergy efficiencies of 12.9, 6, and 5%, respectively. Energy and exergy efficiency of a shallow basin passive solar still have been studied [10]. It was found that with a decrease in absorptivity (from 0.9 to 0.6) with time, the energetic and exergetic efficiencies decrease by 21.8 and 36.7%, respectively. Energy and exergy analysis of passive solar distillation system was carried out [11]. Quantities and places of irreversibility (exergy destruction) have been studied. It was found that irreversibility value for the basin liner, the saline water body, and the glass cover are 3353, 1633, and 362 W/m^2, respectively. Their corresponding exergy efficiencies are found to be 3.91, 17.67, and 42.36% of a total solar exergy input of 6958 W/m^2. Exergy analysis of double slope active solar still under forced circulation mode was studied [12]. Results show that the daily thermal efficiency of solar still varies from 13.55 to 31.07%, and the exergy efficiency varies from 0.26 to 1.34%. Many other works concerning the exergy analysis of solar stills with different configurations, for various operating parameters can be found in [13–17].

Solar distillation is the most economical process as compared to other distillation systems, due to the free energy and the reduced operating costs, especially in isolated regions [18]. Many researchers showed that drinkable water can be produced at low cost using single solar stills. Table 1, shows that the use of single stills gives an affordable cost as compared to other distillation systems.

Studies of heat and mass transfer phenomena, as well as the entropy rate of humid air inside the solar still are of great fundamental and practical importance for engineers and scientists of the field. To the best knowledge of the authors of this paper, there are not enough investigations about this intermediate medium (i.e. humid air) existing between the saline water free surface and the condensing cover. The aim of the paper is to present a comprehensive investigation concerning the humid air behavior inside a passive solar still, based on a previous complete thermal modeling, which was experimentally validated [4].

2. Solar still system and location of study

2.1. Experimental setup

The experimental single slope solar still has a box type structure, and consists of a basin made of fiber reinforced plastic material of thickness

Table 1
Distilled water cost of some desalination systems.

Desalination system	Country	Water cost (US$/l)	Authors
Double slope	Oman	0.074	[19]
Triangular prism still	Australia	0.063	[20]
Hybrid active solar still	India	0.048	[21]
Double slope	Saudi Arabia	0.3125	[22]
Single slope still	Egypt	0.0350	[23]