Desalination 307 (2012) 9–19

Contents lists available at SciVerse ScienceDirect

Desalination

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

Experimental investigation of still performance for different active solar still designs under closed cycle mode

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HIGHLIGHTS

► All models require that air circulation for transporting vapor.
► The air has to be in fuller contact with cold and hot water for highest production.
► The intensity of solar radiation is of prime importance for still productivity.
► Still efficiency goes up, as still operational temperatures increase.
► Still efficiency must be chosen taking into account the limit effects of the system.

ARTICLE INFO

Article history:
Received 30 May 2012
Received in revised form 31 August 2012
Accepted 1 September 2012
Available online 25 September 2012

Keywords:
Active distillation
Humidifcation–dehumidification
Solar energy
Still efficiency
Experimental investigations

ABSTRACT

This paper presents a study into the enhancement of the productivity attained by a proper modification in the system designs. The basic heat and mass transfer expressions for designing solar stills were derived in terms of design and climatic parameters. These solar stills were based on using a direct solar energy collection unit integrated with flash evaporation, distillation equipment and air transportation. The main objective of this study is to estimate the water production and still efficiency for different types of active solar stills in certain locations. In this investigation, proper modifications in the system designs were also made and compared on daily yields and daily still efficiencies. It was observed that a maximum daily yield of 12.37 l was obtained from the circular box solar still unit in Kayseri, Turkey. This study shows that the design of the circular box active solar still also provides the highest overall daily still efficiency, which is about 68.1%, in that of the active solar stills. It is clear that there is a significant effect on daily yield due to the proper modifications in the system designs.

1. Introduction

Fresh water is both the source of life and the most important constituent of the environment. Water is a basic human requirement for domestic, industrial and agricultural purposes. Supplying fresh and healthy water is one of the major problems in different parts of the world, especially in arid, remote areas. Fresh and healthy water is produced from the sewage, brackish and saline water. Sewage waste water is generated from domestic, factories and agricultural activities. Domestic waste water is called as sewage waste water from kitchen and bathroom called gray-water, and from toilet called black-water.

Solar distillation can provide a solution for those areas where solar energy is available in plenty but water quality is not good. Solar distillation is a process to produce the distilled water from sewage, brackish and saline water by using solar energy to provide drinking water, charge the batteries and use for medical and agricultural purposes, etc. Solar distillation processes are a future promising technology. Because solar energy is environmentally friendly, and it is suitable for a few families or small groups in remote areas.

Solar distillation systems are mainly classified as direct (passive) and indirect (active) solar stills. In the passive (direct) solar still, solar radiation is received directly by the basin water without feeding an external energy; consequently, the evaporation leading to a lower productivity. In order to overcome this problem, many active (indirect) solar stills were developed. Recently, some works on indirect (active) solar distillation system were also carried out by various researchers. Indirect (Active) solar thermal desalination technologies include multi-stage flash (MSF), multi-effect distillation (MED), vapor compression (VC) and reverse osmosis (RO), humidification–dehumidification (HDH) and membrane distillation (MD), etc. [1]. These technologies are expensive for small amounts of fresh water and cannot be used in locations such as islands or remote areas where maintenance facilities and energy supply are restricted [2]. All these problems pushed out MED, VC, RO, MD and MSF from remote arid regions and inlands. Solar multi-effect humidification (MEH) units based on the humidification–dehumidification principle are considered

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0011-9164/$ – see front matter
http://dx.doi.org/10.1016/j.desal.2012.09.003

Nomenclature

Ac	solar collector area receiving insolation, m^2
Cp_{air}	specific heat of flowing air, J/kg °C
F_R	collector heat removal factor
L	latent heat of vaporization in the solar still, kJ/kg
h_{fg}	water latent heat of vaporization, kJ/kg
I	insolation received by solar collector, W/m^2
$LMTD$	log mean temperature difference, °C
$\dot{m}_c$	cold water mass flow rate, kg/h
$\dot{m}_h$	hot distilled water mass flow rate in condenser, kg/h
$\dot{m}_e$	sewage water mass flow rate in evaporator, kg/h
$\dot{m}_{coll.}$	mass flow rate of water in flat plate collectors, kg/h
m_v	accumulated production, kg or liter
$\dot{m}_v$	hourly production (vapor condensate rate), kg/h-m^2
$\dot{m}.Cp$	water thermal flow capacity, kW/°C
Qs	heat power from the solar collector, kW
Q_D	solar heat which enters to the still system, kW
P_v	vapor pressure, kPa
P_{atm}	atmospheric pressure, kPa
T	indicate measured temperature for each location, °C
T_1	coldest water temperature in system, °C
T_2	water out temperature from cold heat exchanger, °C
T_3	cooled distilled water temperature to condenser, °C
T_4	warmed distilled water temperature from condenser, °C
T_5	cooled water temperature from evaporator, °C
T_6	heated water temperature to evaporator, °C
T_{amb}	ambient air temperature, °C
T_A	saturated air temperature from evaporator to condenser, °C
T_B	saturated air temperature from condenser to evaporator, °C
T_C	air temperature to solar collector, °C
T_D	air temperature from solar collector (max. system temperature), °C
UA	component thermal conductance, kW/°C
T_A–T_B	operational temperature difference between evaporator and condenser, °C
UA_{cond}	condenser thermal conductance, kW/°C
UA_{evap}	evaporator thermal conductance, kW/°C
UA_{sys}	system thermal conductance, kW/°C
UA_{Trans}	evaporator to condenser conductance, kW/°C
U_L solar	collector heat loss coefficient, kW/m^2°C
$\rho.\dot{V}$	air mass flow rate, kg/sec

Greek symbols

η_c	solar collector efficiency
η_{active}	still efficiency
$\tau\alpha$	collector transmission–absorption product
ω	humidity ratio vapor in air, kgv/kgDryAir
ϕ	Relative humidity

Subscripts

air	air
amb	ambient
atm	atmospher
c	cold
h	hot
cond	condenser
evap	evaporator
fg	fluid–gas
sys	system
trans	transporting

Abbreviations

CBSSU	circular box solar still unit
LMTD	log mean temperature difference
RBSSU	rectangular box solar still unit
STSSU	single tube solar still unit

as the most viable systems among solar desalination units. Solar desalination with a humidification–dehumidification process has proven to be an efficient means of utilizing solar energy for the production of fresh water from saline or sea water [3].

Many studies about various types of HDH desalination systems were carried out [3–33], which was investigated different ways to increase the production of desalinated water and the performance of plants. Performance of the humidification–dehumidification (HD) systems was studied and improved by several researchers [3,4]. Orfi et al. [5] studied a solar HD desalination system theoretically and experimentally. In order to improve the productivity of the system, they utilized the latent heat of condensate water vapor in the condenser to preheat the feed water. Parekh et al. [6] carried out a comprehensive investigation on the background of solar desalination using humidification– dehumidification systems. Many experimental and theoretical results on the solar desalination unit were evaluated by various researchers [7–10] to find out the performance of humidification–dehumidification process. Al-Hallaj et al. [11] undertook an experimental study on a HDH unit. In their unit, the air was circulated by natural or forced convection and was humidified by a constant rate of water obtained either from a collector (indoor type) or from an electrical heater (outdoor type). In an outdoor scenario, their results showed higher fresh water production than that of solar stills. Nafey et al. [12] carried out an experimental work on the HDH process. They found that the effect of air velocity was insignificant, while great influence of inlet water and air temperatures on the production of desalinated water was observed.

Multi-effect humidification–dehumidification is another interesting approach that has been studied by Chafik [7], Mahmoud Ben et al. [13] and Zhan et al. [14]. This technique includes humidification and air heating in several stages which lead to an increase in the moisture density in air flow. A demonstration system based on MEH technology was constructed by Müller-Holst [15] in Jeddah/Saudi Arabia in November 2005, and the designed daily fresh water capacity is 5 m^3. Farid and coworkers had built three MEH desalination units in Iraq (Basrah), Jordan and Malaysia. The unit constructed in Iraq was operated with forced air circulation and produced 12l/m^2d [16]; while the unit constructed in Jordan was operated with both forced and natural draft air circulation [17,18]. Based on the experience of operating these units, a third unit operated with natural draft air circulation was constructed in Malaysia [19,20]. These units were built in order to develop a computer simulation program, which could be used to predict the performance of the HD units operating on natural or forced draft air circulation.

Müller-Holst et al. [21] studied and installed a MEH unit without thermal storage in the island of Fuerteventura with a gain output ratio (GOR) ranging between 3 and 4.5. But this unit did not reach a GOR of 8 obtained in the laboratory at ZAE Bayern at steady-state conditions. In a related study, Ulber et al. [22] investigated and installed in 1997 in Sfax (Tunisia) a unit with a conventional heat storage tank (2 m^3) and heat exchange between the collector circuit (38 m^2) and the distillation circuit. This enabled continuous (24 h/d) distillate production. In 1991, Graef [23] studied a desalination process based on a solar multiple condensation–evaporation cycle (SMEC). Two types of desalination units SMEC 3.6 (50 L/d) and SMEC 200 had been in operation in Sfax (Tunisia) since 1991. Experimental study on these units performed by Ben Bacha et al. [24] had deliberated a condensate production of 4 L/m^2d with a collector efficiency of 46%.