Applied Thermal Engineering 51 (2013) 520–528

Contents lists available at SciVerse ScienceDirect

Applied Thermal Engineering

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

Transient dynamic response of solar diffusion driven desalination

Fadi Alnaimat*, James F. Klausner, Renwei Mei

Department of Mechanical & Aerospace Engineering, University of Florida, Gainesville, FL 32611, USA

HIGHLIGHTS

► The dynamic response for different packed bed materials, wettability, and liquid hold-up are investigated.
► The response time is not sensitive to the packing material.
► Delayed operating mode enhance fresh water production rate.

ARTICLE INFO

Article history:
Received 9 June 2012
Accepted 27 September 2012
Available online 9 October 2012

Keywords:
Evaporation
Condensation
Packed bed
Heat/mass transfer
Direct contact
Transient

ABSTRACT

The dynamic response for the solar diffusion driven desalination (DDD) process has been investigated. The heat and mass transfer within the direct contact evaporator is analyzed by one-dimensional conservation equations. The heat and mass transport models account for the transient variations within the packed bed due to time varying inlet water and air temperatures and humidity. The conservation equations are solved numerically using a finite difference scheme to predict water, air/vapor mixture and packed bed temperatures and humidity ratio within the evaporator and the condenser. The system dynamic response for the packed bed materials, wettability, and liquid hold-up, sudden increase–decrease in the inlet water temperature is investigated. It is found that the response time for the outlet water to reach the steady state temperature in the evaporator is shorter for lower liquid hold-ups. The response time is not sensitive to the packing material. Higher wettability does not affect the response time, but it does result in improved heat transfer with a higher exit air temperature and lower exit water temperature. The steady state temperature in the evaporator is not dependent on the heat capacity of the packing material, and liquid hold up. A delayed operating mode for the solar DDD is introduced to enhance the fresh water production rate. It is found that increasing the initial saline water temperature and decreasing the initial water volume in the seawater tank results in a higher fresh water production rate.

1. Introduction

Direct contact evaporation and condensation for countercurrent flow within packed beds have direct application to various important industrial processes including air stripping, evaporative cooling, and distillation. A typical configuration for direct contact evaporation and condensation involves liquid sprayed over the top of a packed bed that flows downward through the bed due to gravity. The surface of a packing gets wet as water flows downward which provides a very high surface area per unit volume. Air is blown countercurrently upward through the bed. High heat and mass transfer occurs through the gas/liquid interface. Klausner et al. [1] and Li et al. [2] have provided a rigorous mathematical model for analyzing heat and mass transfer for the steady state operation of direct contact packed bed evaporators and condensers. There also exist applications where dynamic operation is more suitable than steady state operation and are characterized by transient heat and mass transfer. An example is the dynamic behavior of solar energy for thermal distillation.

The Diffusion Driven Desalination (DDD) process described by Klausner et al. [1] utilizes direct contact evaporation and condensation for the distillation of the sea and brackish water. The DDD process can be driven by solar heating where the operation is inherently transient. For such operating conditions, a transient heat and mass transfer analysis is required to evaluate its operation over a range of operating conditions. The evaporation and condensation process within the evaporator and condenser primarily depends on the inlet water and air temperature, inlet humidity ratio, and water to air flow ratio. The theoretical models

* Corresponding author. Tel.: +1 352 392 1086; fax: +1 352 392 1071.
E-mail address: falnaimat@ufl.edu (F. Alnaimat).

1359-4311/$ – see front matter © 2012 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.applthermaleng.2012.09.038

developed by Klausner et al. [1] and Li et al. [2] are for constant inlet water and air temperatures to the evaporator and condenser and assume steady state operation; thus a transient theoretical model is needed to study solar driven desalination systems.

The thermal performance of cooling towers has been investigated for a century under steady-state operating conditions. A cooling tower is subjected to varying heat input and operating conditions and a transient model is required to study its thermal response. Transient thermal analyses of cooling towers are important because the ambient air temperature can vary significantly between day and night. The dynamic behavior of cooling towers was investigated recently by Al-Nimr [3,4]. The thermal capacity of the packed bed was included in the analysis. The transient energy equations account for variations in water, air, and packed bed temperature. The overall heat transfer coefficient between water and air was assumed constant. A closed form solution was obtained for the cooling tower steady state performance. A transient solution was obtained using a perturbation method. The transient solution has not been experimentally verified. Marques et al. [5] studied the transient thermal behavior of counter flow cooling towers. Transient equations for air and water in the cooling tower were derived from energy and mass balances. The transient variation of water temperature in the basin of the cooling tower was also accounted for. The heat transfer between the packed bed and the air side was neglected. A 10% step change in the initial conditions of the air flow, water flow, and heat load was used to study the thermal response of the cooling tower. A comparison with experiments is lacking. A rigorous theoretical framework for the transient heat and mass transfer during the evaporation and condensation within backed beds is developed by Alnaimat et al. [6]. The analysis relies on one-dimensional conservation equations, and as such closure relationships are required.

2. Description of the solar diffusion driven desalination

The solar DDD process is primarily comprised of a direct contact evaporator and condenser and a solar collector. The saline water is circulated through a flat plat solar collector to be heated. A schematic diagram of the direct contact evaporator and condenser desalination facility is shown in Fig. 1. The direct contact evaporator and the condenser are filled with packed bed material that allows direct contact between air and water. The evaporator admits the heated saline water and sprays it at the top of the packed bed using a nozzle. Air is driven via a fan at the bottom of the evaporator to circulate the air through the facility. The drawn air is flowing counter-currently to the falling water leading to humidification of the air. The humidified air discharges the evaporator at the top as fully saturated and then enters the direct contact condenser. Cold fresh water is sprayed at the top of the condenser; thus the humidified air is brought into direct contact with cold fresh water. The humidified air stream passes through the condenser and loses some heat to the cold fresh water resulting in vapor condensation. Distillate water is collected at the basin of the condenser and sent to a fresh water tank. The use of recirculated air instead of fresh air improves the system performance because the recirculated air temperature is always higher than that for fresh outside air. Having higher inlet air temperature in the evaporator results in improved evaporation, and thus higher water production. Also, the heat will be contained within the system for the recirculated air configuration, which improves the thermal effectiveness of the desalination process.

3. Mathematical model for dynamic operation

The operation of the distillation process is inherently transient since it is driven by solar heating; a transient heat and mass transfer

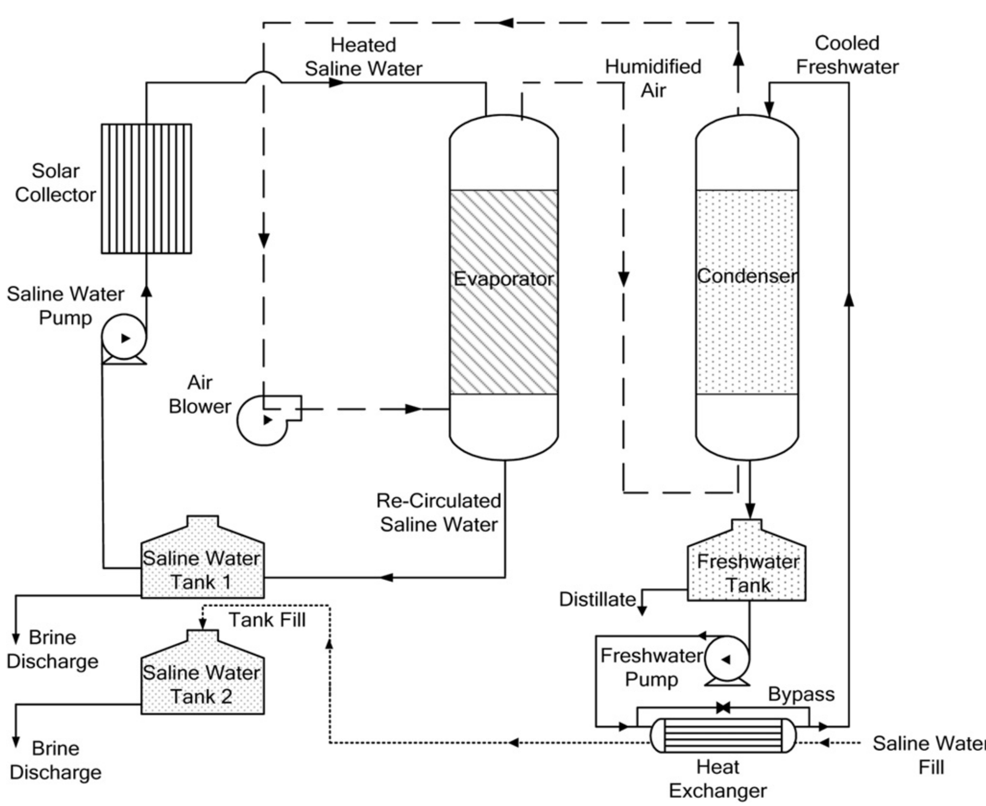

Fig. 1. Schematic diagram of the experimental direct contact evaporator and condenser desalination facility.