Energy Conversion and Management 127 (2016) 667–678

Contents lists available at ScienceDirect

Energy Conversion and Management

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

An experimental investigation of a novel design air humidifier using direct solar thermal heating

Hafiz M. Abd-ur-Rehman [a,b], Fahad A. Al-Sulaiman [a,c,*]

[a] Mechanical Engineering Department, King Fahd University of Petroleum & Minerals (KFUPM), Dhahran 31261, Saudi Arabia
[b] School of Mechanical & Manufacturing Engineering (SMME), National University of Sciences & Technology (NUST), H-12 Campus, Islamabad, Pakistan
[c] Center of Research Excellence in Renewable Energy (CoRERE), Research Institute, King Fahd University of Petroleum & Minerals (KFUPM), Dhahran 31261, Saudi Arabia

ARTICLE INFO

Article history:
Received 15 February 2016
Received in revised form 8 August 2016
Accepted 17 September 2016

Keywords:
Solar thermal energy
Water desalination
Multi-stage humidifier
Humidification efficiency
Bubble column
Fresnel lens

ABSTRACT

In this study, a novel solar heated multi-stage bubble column humidifier is designed and tested. The overall objective of this work is to investigate the main operating parameters of the new humidifier. The study addresses the significance of the perforated plate geometric features, optimum balance of air superficial velocity and water column height, and the influence of inlet water temperature and inlet air relative humidity on the performance of the humidifier. The day round performance of the humidifier is investigated in single stage, two stage, and three stage configuration, in which each configuration was tested with and without the integration of the Fresnel lens. Findings show that the average day round absolute humidity, without Fresnel lens, increased up to 9% for the two stage configuration and 23% for the three stage configuration as compared to the single stage configuration of the humidifier. The integration of the Fresnel lens further increased the absolute humidity up to 25% as compared to the results obtained without the integration of the Fresnel lens under the same prevailing conditions, which is significant. Moreover, the current humidifier shows a higher humidification efficiency in the climatic conditions that have a lower inlet air relative humidity. Furthermore, the finding demonstrates that the newly developed multi-stage bubble column humidifier has better performance as compared to the conventional single stage bubble column humidifier. The findings from this study are of pivotal importance to understand the optimum operating conditions of the humidifier for its possible integration with the dehumidifier. Consequently, an improved humidification-dehumidification desalination system attained.

1. Introduction

The fresh water is the essence of life and its scarcity is the most threatening concern for mankind. To alleviate the worries of the existing and approaching fresh water crisis, many countries have installed seawater desalination plants to yield the potable water. These plants are highly energy intensive and economically suited only on large scales [1]. However, desalination systems are more required on small scales for decentralized supply of fresh water in remote areas [2]. Therefore, it is highly desirable to develop an efficient, reliable, and cost effective decentralized water desalination system to make the clean water accessible for remote communities.

Solar humidification-dehumidification (HDH) is an appropriate choice for a decentralized small scale water desalination system, especially in remote regions where inexpensive land and abundant solar radiations are available [3]. Other advantages of the solar HDH system include its simple functionality, moderate investment, and usage of low grade heat sources [4]. Several studies are available that explore the prospects of utilizing solar energy in HDH system. Parakash et al. [5] carried out a detailed literature review on the potential of solar HDH system for small-scale decentralized water production. The review reported a comprehensive comparison of different HDH systems and concluded that the multi-effect close-air open-water (CAOW) water heated HDH system is the most energy efficient system. Moreover, the author's proposed the methods that can further improve the performance of HDH systems. Recently, Giwa et al. [6] carried out a literature review on the advancements in HDH systems and discussed the improved designs that helped in achieving the better performance. One of the improved design is the use of bubble column as a humidification device for an HDH water desalination system. In the bubble column humidifier, air is passed through perforated plates to form bubbles in the hot water column. As the air bubbles propagate

* Corresponding author at: Mechanical Engineering Department, King Fahd University of Petroleum & Minerals (KFUPM), Dhahran 31261, Saudi Arabia.
E-mail address: fahadas@kfupm.edu.sa (F.A. Al-Sulaiman).

http://dx.doi.org/10.1016/j.enconman.2016.09.053
0196-8904/

through the hot water column, simultaneous heat and mass transfer take place where air becomes hot and humid at the outlet of the humidifier. The higher rate of heat and mass transfer in a bubble column inspired the researchers to extensively practice these devices as a multiphase reactor in chemical process like Fisher-Tropsch process, in metallurgical and many biomedical applications [7]. However, the use of the bubble column humidifier in HDH water desalination is very limited and there are very few studies that investigate the bubble column as a humidifier for HDH water desalination system. El-Agouz and Abugderah [8] carried out an experimental investigation of a single stage bubble column humidifier. They considered the effect of water inlet temperature, air inlet temperature, and air inlet velocity on the humidifier efficiency. Their results specified that the performance of the bubble column humidifier is considerably increased by increasing the air inlet velocity and the water inlet temperature. The air inlet temperature has a slight influence on the air vapor contents difference. The effect of water column height and air inlet humidity was not considered in this study. Zhang et al. [9] performed an experimental study on a single stage bubble column humidifier that aimed to achieve a high water vapor concentration in the air at the exit of the humidifier with a less pressure drop and a low blower power consumption. The results showed that the increase in the water level and air flow rate caused a greater pressure drop and a higher blower energy consumption. The moisture contents at the exit of the humidifier were increased with the increase in water and air temperatures. Khalid et al. [10] performed an experimental study on a single stage bubble column humidifier that was integrated with solar water heater. The study claimed to achieve a daily productivity of 21 kg with a gained output ratio (GOR) of 0.53 at the water inlet temperature of 62 °C. The study also addressed the effect of geometric features of the sieve plate on the performance of the system and concluded that the best performance was achieved using 1 mm hole diameter. However, the system experienced a high pressure drop due to small hole diameter and high water column height. Liu and Sharqawy [11] performed an experimental study in which they analyzed the effect of pressure on the performance of bubble column HDH system under varying operating conditions. The study concluded that the effectiveness of the humidifier is increased when it is operated under sub-atmospheric pressure. Moreover, the author's developed a modified effectiveness-number of transfer units (ε-*NTU*) model to analyze the performance of bubble column HDH system.

In most of the aforementioned experimental investigation of the bubble column humidifier, water is heated by an electric heater that limits the use of these HDH systems in remote areas where electricity availability is scarce. Therefore, a novel bubble column humidifier is developed that is operated through solar thermal energy as the main source of energy input. This study addresses the novelty of the developed humidifier design in terms of direct solar thermal heating and multi-stage functionality. The significance of the perforated plate geometric features, the optimum balance of air superficial velocity and water column height, and the influence of inlet water temperature and inlet air relative humidity are evaluated to understand the optimum operating conditions of the developed humidifier for its possible integration with the dehumidifier. Consequently, an improved HDH water desalination system is achieved.

2. Experimental setup

In order to investigate the performance of the humidifier, a laboratory scale setup was designed and built as shown in Figs. 1 and 2. Fig. 1 is the schematic illustration of the humidifier design and Fig. 2 is the real photograph of the experimental setup. The frame of the experimental setup was constructed of 10 mm thick Plexiglas sheet. The bubble columns of 300 mm × 300 mm cross section were constructed in a stepped configuration. The perforated plate was made of a 2 mm thick black acrylic Plexiglas. The perforated plate splits the bubble column into lower and upper compartments. Air is introduced by a 400 W adjustable blower to the lower compartment of the bubble column through a 25 mm diameter CPVC (Chlorinated polyvinyl chloride) pipe. The lower compartment is used to distribute the air stream uniformly through the perforated plate. The upper compartment of the bubble column is used as a pool for hot water through which air propagates to form bubbles.

In this humidifier, the absorber plate and bubble columns were incorporated in a single frame design. The absorber plate is titled to an angle equal to the latitude of Dhahran (26.3°), Saudi Arabia, to absorb the maximum solar radiations. The tilted absorber plate acts as a sloped surface to create a thin film of water over the absorber plate. The minimum water depth over the absorber plate leads to a better heat transfer and, consequently, a higher water temperature is achieved at the exit of absorber plate. The heated water coming from the absorber plate passes over the stepped configuration of the bubble columns. Each bubble column is equipped with water control valves at different heights that can be connected to the next stage or can be drained outside the setup. In single stage humidifier configuration, the desired water column height is achieved by draining the water through control valve at that desired height while closing all other valves below it. In multi-stage humidifier configuration, the water control valves are connected to the next stages and opened at the desired water column height to bypass the water to the next stages. In this way the water is maintained at desired height is different stages and water flows in stepped configuration under the force of the gravity. Another advantage of this humidifier is its multistage functionality, which results in improving the performance. In the single stage configuration, the water and air stream homogeneously mixed in a single bubble column and experience a large temperature difference. Therefore, the air stream is not able to reach the water inlet temperature in single stage humidifier. On contrary, the multistage stepped configuration of the humidifier segments the water and air stream paths to provide a lower temperature difference in each stage. Consequently, the air stream is heated in each stage and leave the humidifier at a temperature that is very close to the water inlet temperature. The temperature variations in the water and air stream along the steps of the humidifier is shown in Fig. 3.

The multistage stepped configuration also helps in attaining a higher absolute humidity by both heating and humidifying the air throughout its full path inside the humidifier. Fig. 4 depicts the air humidification process in the humidifier operated in the single stage, two stage, and three-stage configuration. The air humidification process in the single stage humidifier configuration is represented by the line A-B on the psychometric chart. The air humidification process in the two-stage humidifier configuration is represented by the line A-2′ for the second stage and the line 2′-B′ for the first stage on the psychometric chart. As the number of stages are increased from 1 to 2, hot humid air at the exit of the second bubble column stage (represented by point 2′ on the psychometric chart) also passes over the neighboring first bubble column stage (represented by line 2′-B′ on psychometric chart) that is operating at a higher temperature as compared to the second-stage configuration. This allows the air to absorb more moisture and achieve a higher absolute humidity at the exit of humidifier operated in the two-stage configuration. Similarly, when the humidifier is operated in the three-stage configuration, the air at the exit of the third bubble column stage (represented by point 3″ on the psychometric chart) also passes over the