Renewable Energy 69 (2014) 253–259

Contents lists available at ScienceDirect

Renewable Energy

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

Technical note

Experimental investigation of a novel multi-effect solar desalination system based on humidification–dehumidification process

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ARTICLE INFO

Article history:
Received 23 October 2013
Accepted 24 March 2014
Available online

Keywords:
Solar desalination
Humidification–dehumidification
Multi-effect
Higher temperature dehumidifier
Lower temperature humidifier

ABSTRACT

This paper presents an experimental investigation of a novel multi-effect solar desalination based on humidification–dehumidification process. The main objective of this work is to determine the operational and performance characteristics of the system with use of packed porous plastic balls and finned heat exchangers. The effect of operating parameters such as the heating temperature, the seawater flow rate (M_w) and the air flow rate (V_a) on the system performance is studied. The performance indicators GOR (defined as the ratio of the condensation heat of water produced relative to the heat input) and yield of the device are calculated from the measured temperatures and flow rates for different operating conditions. A set of performance curves under the different desired conditions are presented. The experimental results indicate that the yield of the system increases with increasing the water flow rate and the air flow rate; the yield of the unit can reach 63.6 kg/h at the water flow rate of 1000 kg/h. Owing to re-utilisation of condensation heat between two desalination loops, the GOR of the multi-effect solar desalination system can reach about 2.1. A further improvement of this multi-effect solar humidification–dehumidification desalination could be expected through optimisation of design and operation.

1. Introduction

For a solar humidification–dehumidification desalination system, the basic processes such as solar collection, evaporation and condensation can be enhanced respectively to increase the thermal utilization efficiency. In addition, a humidification–dehumidification desalination system has several appealing and distinguishing features including its simple layout, flexibility in capacity, low temperature operation, moderate installation, cheap operating cost and ability to be combined with renewable energy sources. Solar energy is one of the ideal renewable energy resources to provide many advantages compared to fossil fuel. Thus, solar energy provides a solution to cover the energy needed for a humidification–dehumidification desalination system with no negative impact on the environment. Based on the characteristics mentioned above, a solar desalination system based on humidification–dehumidification principle is considered as the most viable option among solar desalination technologies, and become a hot pursuit by many investigators [1–4].

Up to now, many experimental studies and theoretical analysis have been carried out on the purpose of the improvement of the design, operation, performance evaluation and efficiency [5–9]. Prakash et al. [10] proposed a significant parameter known as the 'modified heat capacity rate ratio' in the thermal design of humidification–dehumidification systems and in simultaneous heat and mass exchange devices. A pilot-scale humidification–dehumidification unit with a peak production capacity of 700 L/day has been constructed and detailed experiments have been performed on this unit. It has been observed that the humidification–dehumidification systems without mass extractions need to be operated at a top brine temperature as high as possible in order to ensure a high GOR which is the ratio of the condensation heat of water produced relative to the heat input. A new method for exergy analysis of humidification–dehumidification desalination systems was described by Ashrafizadeh et al. [11], following which various parametric effects on exergy losses was investigated. Results indicated that the mass transfer phenomenon does not have any effect

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http://dx.doi.org/10.1016/j.renene.2014.03.048
0960-1481/

on the total exergy losses of the humidification–dehumidification systems and flow rate of the unheated fluid and the maximum temperature of the system have key roles in the total exergy losses. Then the dehumidifier in the air-heated systems has a larger role than the water-heated systems in the irreversibility. An experimental investigation of a new solar desalination prototype using humidification–dehumidification principle outdoors was conducted by Zhani et al. [12]. The temporal evolutions of the temperature of air and water and the relative humidity at the inlet and the outlet of each component of the system have been studied. The experimental results showed that the outlet and the inlet temperatures at different component levels have the same trends as solar radiation, and the ambient air temperature has insignificant effect on thermal performance of the unit.

Farsad et al. [13] carried out a study on the thermodynamic analysis of a desalination unit with humidification–dehumidification cycle. During the study, solar energy was considered as a source of heat. The mass and energy balance equations have been developed for the humidifier, condenser and other cycle components. Its aim was to analyse cycle parameters and to determine the yield of fresh water. In addition, optimum conditions of the plant have been achieved by using design of experimental (DOE) method. A 1000 L/day solar humidification–dehumidification system was constructed and analysed by Yuan et al. [14]. This system was composed of a solar air heater field, a solar water collector, a humidifier–dehumidifier unit, a pre-treatment and other subsystems. Performance of the solar air heater field and the humidifier was investigated by experimental tests. The results showed that water production of the system could reach 1200 L/day under the average intensity of solar radiation of 550 W/m^2.

In order to enhance utilization efficiency of the latent heat of condensation, gain more fresh water output per square metre area of solar collector and reduce the energy loss of humidification–dehumidification desalination unit, a serious of designs of multi-effect solar humidification–dehumidification desalination system were presented by some researchers, and the process efficiency, the heat and mass transfer process and the relation among the different control parameters of the unit were studied. A study of a new generation of water desalination installation by solar energy using the SMCEC (Solar Multiple Condensation Evaporation Cycle) principle was reported by Ben et al. [15]. The fresh water obtained by this new principle favours its use for producing water for drinking and irrigation. Modelling, simulation and experimental validation for this type of installation were carried out, and the models of the different sections of the unit were developed. The obtained results were then compared against the experimental results. The experimental design and computer simulation model of a multi-effect humidification–dehumidification (MEH) solar desalination system has been presented by Garg et al. [16]. The circulation of air in the humidifier and dehumidifier towers was being maintained by natural convection. The system modelling was constructed based on various heat and mass transfer equations and their numerical solutions. And the experimental results were plotted along with theoretical results, to examine the model validity.

Further work in improving the efficiency of multi-effect solar humidification–dehumidification desalination system was carried out by Hou et al. [17]. In such a unit, multi-effect humidification–dehumidification desalination process was plotted according to pinch technology, and then the water rejected from multi-effect humidification–dehumidification desalination process was reused to desalinate in a basin-type unit further. Due to the multiple use of the latent heat of condensation, the GOR of the system could reach 2–3. A model and a structured procedure to optimize the shape and structure of a multi-effect humidification–dehumidification desalination unit were introduced by Morteza et al. [18]. Based on considering maximum production rate as the objective function, optimum design parameters of the multi-effect humidification–dehumidification desalination unit were derived by using the genetic algorithm method under the fixed total volume condition. The results showed that the inlet cold and hot water temperatures and the column heights play important roles in the constructal design of a multi-effect humidification–dehumidification desalination unit.

However, the previous researches on the multi-effect solar humidification–dehumidification desalination system have some defects, the latent heat of vapour condensation is not utilized sufficiently, thus leading to low usage rate of solar energy and low water yield per unit area of solar collector. Based on the previous researches, this paper therefore presents a novel multi-effect solar humidification–dehumidification desalination device. The present work carried out some investigation on a novel generation of water desalination system. The paper describes the desalination process of the multi-effect solar humidification–dehumidification desalination system and assesses the performance of the device under different operation conditions.

2. Description of the experimental set-up and working principle

2.1. Structure parameters and working principle

The humidification–dehumidification process is based on the fact that the moisture content of air increases progressively with elevated temperature. For example, 1 kg of dry air can carry almost 0.67 kg more vapour when its temperature increases from 60 to 85 °C.

The system presented in this paper consists of three closed loops: a solar loop that can produce hot water and two water desalination loops with the function of producing desalinated water. The solar loop is a thermosyphon water heater connected with a heat exchanger to deliver heat to the seawater. The desalination loops include several hot seawater sprayers, a higher temperature humidification tower, a higher temperature dehumidification tower, a lower temperature humidification tower and a lower temperature dehumidification tower, which are configured to form an upper loop and a lower loop. Air is circulated by fans within each loop. Fig. 1 illustrates a schematic diagram of the experimental set-up and Fig. 2 shows its photograph.

In the higher temperature and lower temperature dehumidification sections, the two heat exchangers are made of copper tubes with corrugated aluminium fins and they are connected to each other in series. To increase the contact surface between air and seawater, the porous plastic balls 9 were packed in the higher temperature and lower temperature humidification sections to achieve a larger wetted surface and an efficient humidification of the air. These humidification and dehumidification sections are contained in two thermally insulated cylinders which were constructed of 2 mm stainless steels by welding and had the insulation thickness of 25 mm.

The operating principle of the experimental unit can be seen from Fig. 1. Firstly, the seawater is fed to the lower temperature dehumidifier to condense the water vapour of the moist air coming from the lower temperature humidifier. At the exit of the lower temperature dehumidifier, a small part of seawater is rejected to the outside and the remainder enters the higher temperature dehumidifier to condense the water vapour in the moist air flowing from the higher temperature humidifier. After that, the heated seawater is divided into two parts. One enters the higher temperature humidifier tower through sprayer 8 and the other flows into the lower temperature humidifier tower.