Energy Conversion and Management 85 (2014) 140–145

Contents lists available at ScienceDirect

Energy Conversion and Management

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

Experimental investigation of a portable desalination unit configured by a thermoelectric cooler

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ARTICLE INFO

Article history:
Received 13 February 2014
Accepted 19 May 2014
Available online 13 June 2014

Keywords:
Peltier
Thermoelectric
Desalination
Humidification
Dehumidification

ABSTRACT

Possible use of a novel portable desalination system was investigated experimentally. The system is based on humidification–dehumidification principle and thermoelectric cooling technique. A thermoelectric cooler was integrated into the system to enhance the process of both humidification and dehumidification. A prototype was fabricated and its performance was tested for various working conditions of the prototype to observe complex relation between psychrometric and thermoelectric phenomena. The effect of feed water mass flow rate and air flow velocity on the COP value of the thermoelectric cooler and clean water production of the system were examined. The maximum daily yield of the system and the COP value of the thermoelectric cooler unit were recorded as 143.6 g and 0.78, respectively.

1. Introduction

Water is an indispensable need for life and the development of civilization and industry. However, water sources are rapidly declining because of gradually increasing human population, industrial pollution, urbanization, inappropriate agricultural policies and natural disasters. Desalination of brackish water/sea water is a sustainable way to meet water demand of people in case of water shortage.

The process based on Humidification–Dehumidification (HDH) principle is being in the forefront of studies on small-scale systems. HDH techniques have been subject of many studies in recent years due to the low-temperature energy (geothermal, solar, waste energy) use, simplicity, low cost in installation and operation. These types of systems also work at atmospheric pressure; hence they do not need mechanical energy except for circulation pumps and fans. Therefore, their design, construction and operation are easy. The technical infrastructure of developing countries makes it suitable for the production of these kinds of systems for household use. The system is modular; hence it is possible to increase system capacity with additional collectors and additional HDH cycles. Historical development, current status, opportunities for future use, state of art and the usage of the renewable energy sources in desalination processes were addressed in papers [1,2] and a book [3].

Dai and Zhang [4] presented an experimental study on HDH desalination system. They observed that feed water mass flow rate, feed water temperature and air mass flow rate have some significant influence on the system productivity. They also reported the optimum rotation speed of the fan corresponding to an optimum air mass flow rate. Al-Enezi et al. [5] conducted an experimental study on a HDH desalination system to investigate the effect of various operating parameters on the system efficiency. The parameters of interest for a low-capacity system are feed water temperature and mass flow rate, air mass flow rate and cooling water temperature. They found that the feed water temperature has considerable influence on the amount of product. Nafey et al., [6,7] theoretically and experimentally studied the performance of a desalination system based on HDH principle. The system was configured by a flat plate solar air heater and a parabolic concentrated solar water heater. Only air heating, water heating, and air–water heating with open circuit and closed circuit configurations were considered in the theoretical study. The validity of the theoretical model was presented in the experimental study. In both studies, they investigated the effect of feed water mass flow rate, air mass flow rate, cooling water mass flow rate and meteorological conditions on the performance of the systems. Orfi et al. [8] investigated performance of a HDH desalination system consisting of flat plate solar collectors for water and air heating. They calculated the transient efficiency of humidifier and

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http://dx.doi.org/10.1016/j.enconman.2014.05.071
0196-8904/

Nomenclature

COP	coefficient of performance	I	DC current supplied by power supply (A)
$\dot{m}$	feed water mass flow rate (kg/s)	V	DC voltage supplied by power supply (V)
c_p	specific heat of water (kJ/kg K)		
Δt	water temperature difference between inlet and outlet of water block (°C)		

determined optimum air/water mass flow rate for maximum productivity. Yamalı and Solmuş [9,10] theoretically and experimentally investigated a HDH desalination system configured with a double pass solar air heater. They developed a mathematical model to examine different design and operational parameters on the system performance. They found that system productivity increase with increasing feed water mass flow rate and feed water temperature. Nawayseh et al. [11] fabricated three different sized HDH desalination systems. They considered closed air cycle and natural draft operation. They also made further research with steady and unsteady computer simulation [12]. Kudish et al. [13] designed and constructed an evaporation/condensation desalination system from polymeric materials. Natural draft was considered to vapor transport. They examined the optimum design parameters and operation conditions by means of experimental and theoretical investigation.

Thermoelectric coolers (TECs) consist of n-type and p-type semiconductor material connected electrically in series. Temperature difference occurs due to Peltier effect while DC electric current is applied. TECs are very small, quiet, maintenance free and reliable electronic devices. They do not need to CFC or any other refrigerant gases. Due to these advantages, TECs are used for many refrigeration applications. On the other hand, their efficiencies are very low. Hence, this undesirable feature limits the widespread use of TECs. Development on material sciences would make a breakthrough on TECs applications. Basic knowledge and the overview of TECs applications are discussed by Riffat and Ma [14,15].

Vian et al. [16] investigated the performance of a prototype dehumidifier with TECs. They mainly focused on the optimization of the TECs, fan supply voltage and evaluated the COP value of the system and condensed water flow rate. They indicated that TECs may have significant potential in the use of dehumidification systems. Milani et al. [17] investigated the feasibility of a dehumidification system using TECs to produce fresh water from atmospheric moisture. They developed an algorithm to correlate psychrometric parameters of the system and determined the amount of fresh water product, required energy and the cost of fresh water product. Esfahani et al. [18] tested a new portable solar desalination system with a TEC. Water is heated by a portable parabolic collector and evaporated in a black painted evaporation zone. The TEC is responsible for condensation process. They observed that ambient temperature and solar intensity have positive effect on productivity. On the other hand, the productivity is adversely influenced by increasing wind speed. Rahbar and Esfahani [19] investigated a novel portable solar desalination system with a TEC and a commercial heat pipe. The TEC helped to condensation and heat pipe removed heat from the hot side of TEC.

These previous studies show that several investigations on the HDH desalination systems have been conducted by numerous researchers in the recent years. However, little attention has been given on portable desalination systems and the application of TECs on desalination systems. Further studies are needed, in order to improve present understanding of productive use of the TECs in desalination processes. Apart from the other studies, a TEC is integrated into the HDH desalination system to provide a cold surface for condensation (dehumidification) and warm up feed water for humidification. This integration allows us to use waste heat of TEC and hence, reduce the size and weight of the desalination systems for portable usage. Experimental results are presented and the feasibility of proposed system is discussed as follows.

2. Description of the experimental setup

The system is based on the idea of open water-open air cycles and mainly consisted of a humidifier, a dehumidifier, a heat sink-TEC-water block unit and a fan. A schematic diagram and photos of the experimental setup are illustrated in Fig. 1.

A single TEC module was integrated into the HDH desalination system. The TEC (TEC1-12709) was 40 mm long, 40 mm wide and 3.4 mm high. The cold and hot sides of the TEC were used for dehumidification process and heating of feed water, respectively. A portable desalination unit was constructed by 3 mm thick Plexiglas. All of the system components were insulated by 2 cm thick polystyrene foam with thermal conductivity 0.033 W/m K (Fig. 1b).

Operating principle of the system may be summarized as follows. Air at the ambient conditions is forced to flow through a 30 cm long, 15 cm wide and 30 cm high cellulose pad humidifier. A 30 W adjustable rotational speed air fan is mounted at the exit of the dehumidifier to force air into the system. An aluminum water block is used to remove waste heat from the hot side of TEC (Fig. 1d). The waste heat is used to increase the temperature of feed water. The heated feed water is distributed by a spreader into the cellulose pad humidifier for better mixing of air and water. The air comes in contact with the wetted surface of the cellulose pad humidifier. As a result, the air is humidified by warm water. The humidified air enters into an aluminum heat sink condenser (dehumidifier). The total heat transfer area of condenser is 0.192 m^2. The condenser is fixed at the cold side of TEC with thermal grease. The humidified air passes through the condenser surface where water vapor condenses and turns into fresh water. Collected brine at the bottom of the humidifier is drained from the system. Clean water is gathered from the bottom of the condenser. In order to ensure correct air velocity measurement, a pipe having 5 cm radius is attached to the humidifier.

Four separate K type thermocouples were used to determine the inlet and outlet temperatures of the water block, the cold side temperature of the TEC and the outlet water temperature of the humidifier. The amount of heat rejected from the hot side of the TEC was calculated by using the inlet and outlet water temperatures of the water block. Air temperature and relative humidity at the inlet of humidifier, the outlet of humidifier and the outlet of dehumidifier were monitored by three separate humidity sensors. Air velocity was measured by a hot wire anemometer placed at the inlet of the humidifier. A rotameter was used to measure feed water mass flow rate. The TEC was supplied by an adjustable DC power supply.

All measurement points and equipment are shown in Fig. 1 and their specifications are presented in Table 1. Maximum experimental uncertainty of COP was calculated as 9.95% by Eq. (1). If a result R is to be evaluated by a function $R = f(x_1, x_2, x_3, \ldots, x_n)$ from a single set