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Effective use of thermal energy at both hot and cold side of thermoelectric module for developing efficient thermoelectric water distillation system

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ABSTRACT

An efficient thermoelectric distillation system has been designed and constructed for production of drinkable water. The unique design of this system is to use the heat from hot side of the thermoelectric module for water evaporation and the cold side for vapour condensation simultaneously. This novel design significantly reduces energy consumption and improves the system performance. The results of experiments show that the average water production is 28.5 mL/h with a specific energy consumption of 0.00114 kW h/mL in an evaporation chamber filled with $10 \times 10 \times 30\ mm^3$ of water. This is significantly lower than the energy consumption required by other existing thermoelectric distillation systems. The results also show that a maximum temperature difference between the hot and cold side of the thermoelectric module is 42.3 °C, which led to temperature increases of 26.4 °C and 8.4 °C in water and vapour, respectively.

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1. Introduction

The demands for freshwater over the past 10 years have been rising dramatically in many regions of the world. The water is not only vital for life, but also for domestic, industrial and agricultural purposes [1]. The shortage of freshwater imposes a serious problem to the survival and quality of life of the mankind. Freshwater makes up a very small fraction of all water on the planet. The oceans contain approximately 97% of the available water of the earth and about 2% of the remaining water is reserved as ice in Polar Regions. Thus, only around 1% of the water on earth is freshwater that are drinkable [2]. One solution to deal with the freshwater resource depletion is to desalinate seawater [3]. The number of desalination systems has increased continuously in the past years totalizing a daily production of 66.4 million m^3 of desalinated water worldwide in 2010 [4], 71.9 million m^3 in 2011 [5] and 81 million m^3 in the first quarter of 2014 [6].

Desalination technologies are grouped as thermal distillation (phase-change) and membrane desalination (no phase-change), and these are further divided into subgroups. The main thermal distillation technologies are multi-stage flash (MSF), multi-effect distillation (MED), vapour compression (VC) and still distillation (SD). The main membrane technologies are reverse osmosis (RO) and electro-dialysis (ED) [7]. But the cost associated with energy consumption of these methods is high and also have environmental drawbacks due to the use of fossil fuels [8]. Over the past few years, the thermal distillation using solar energy has been investigated [1–8]. The performances of solar energy assisted distillation can be further improved by using the cooling technology to lower temperature of the condenser. Thermoelectric coolers are a solid-state heat pumps based on the Peltier effect [9,10]. They have no moving parts, and are inherently reliable, noiseless, compact, easily controllable, and environmentally friendly [11–13]. Because of these advantages, using thermoelectric devices for water distillation has been an interesting topic in the field.

Many attempts have been made to increase water productivity and performance using thermoelectric modules. Esfahani et al. made a portable active 4-litre solar still using a thermoelectric cooler to enhance the performance of the unit on winter days [14]. The experiments were collected every winter day from 9 a.m. to 4 p.m. They reported that the average daily productivity of the solar still in nine winter days was 1200 mL/m^2. Rahbar and Esfahani studied a portable solar still utilizing a heat pipe and thermoelectric module [15]. The heat-pipe was used to enhance heat transfer on the hot side of the thermoelectric cooler. The maximum daily yield of fresh water was 280 mL/m^2. Their further work show that the minimum and maximum daily productivity of the asym-

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metrical solar still was approximately 225 mL and 500 mL for the solar intensity of 20,500 and 25,500 J/m^2, respectively [16]. Yıldırım et al. investigated experimentally a portable desalination unit using a thermoelectric cooler [17]. The power consumption of this is 110.26 W and the maximum daily yield of the system was 748 mL/m^2. Vián et al. designed and built a thermoelectric dehumidifier based on thermoelectric cooling technology [18]. The test results show that the rate of water condensation was 0.969 L/day at a power consumption of 100 W. Dehghan et al. employed a thermoelectric module in a novel portable solar still to raise the temperature difference between evaporating and condensing zones [19]. The daily productivity was 2.4 L/m^2/day.

In all those systems, the thermal energy produced at the hot side of the thermoelectric module was wasted and rejected into environment. The unique feature of the thermoelectric distillation system reported in this study is a novel design that facilitates the heat at the hot side of the thermoelectric module to be circulated back to the water tank to enhance water evaporation, while simultaneously using the cold side to lower the temperature of the condenser to improve water condensation. As a result, both the water productivity and efficiency of water distillation can be significantly improved.

2. Engineering design and system description

The key design objective is to ensure that the desirable energy flow in the evaporation-condensation processes can be achieved by appropriate incorporation of thermoelectric module in a water distillation system. Fig. 1 shows the assembly drawing of the system.

The basin was filled with 300 mL of sample water, which occupies an area of 10×10 mm^2 and a height of 30 mm. In order to allow the condensate to flow down to collecting channel without mixing with the sample water, sufficient distance between the condenser and the surface of the sample water is necessary. Similarly, a gap between the sample water surface and collecting channel is needed. A minimum clearance of 1.5 mm is used in this design as shown in Fig. 2. The distance between the inlet and outlet of water pipes is 9 mm (measured from centres of the pipes). Both water pipes have a diameter of 8 mm.

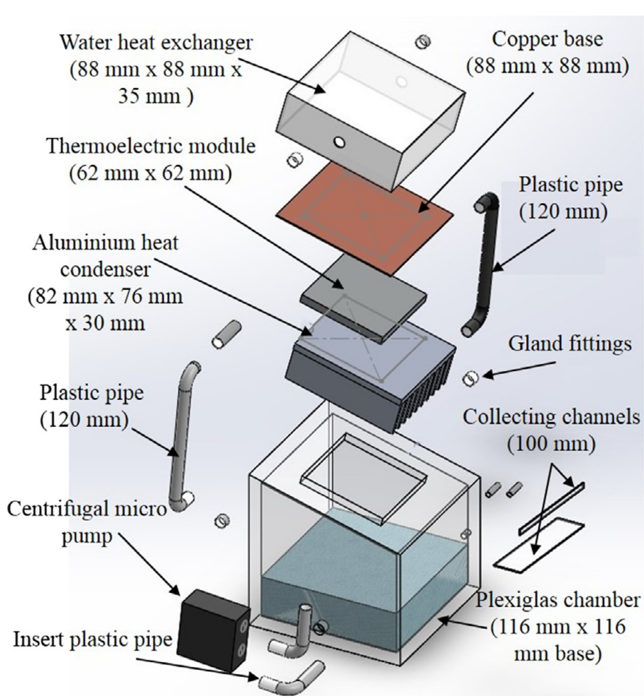

Fig. 1. Assembly drawing and dimensions of the key components in thermoelectric distillation system.

An aluminium heat sink with fins is connected to the cold side of the thermoelectric module to condense the water vapour and a heat exchanger is used to cool the hot side of thermoelectric module and the thermal energy dissipated from the hot side of thermoelectric module is circulated to heat the feed water. Water flows from the top of the unit over a copper heat exchanger to the bottom basin. A small pump is used to pump the unevaporated water to the top of the unit. The water recirculation is a significant aspect of the system in order to reduce the energy consumption by eliminating the need of a separate heater unit for vapour production. Fig. 3 shows the cross-sectional view of the system and water recirculation route.

3. Experimental setup

In order to reduce the heat losses from the hot water and vapour and to observe the evaporation and condensation processes, all walls were made of 8 mm thickness clear Plexiglas and 5.6 mm thick inclined ceiling with an angle of 15° (see Fig. 4a). The condensing zone consists of an inclined and a vertical region of an aluminium heat sink, which are cooled by thermoelectric module. The aluminium heat sink has an area of 0.041 m^2 with 10 fins, which are 25 mm long and 1.5 mm thick (see Fig. 4b). A thin layer of heat sink compound was used between the aluminium surface and the cold side of the thermoelectric module. The smoothness of the aluminium surface was carefully selected to ensure high hydrophobic that will maintain water drops as spherical shape rolling off the condenser surface relatively easily.

A copper heat exchanger is mounted onto the hot side of the thermoelectric module to transfer heat from the hot side of the thermoelectric module to the circulating water. The water level in the system was maintained by refilling of the water from a small tank situated at the top. The water flows from the top of the system over a copper heat exchanger to the bottom basin. The condensed water is collected on a thin Plexiglas plate below the aluminium heat sink. Also, collecting channels are positioned on the vertical walls for collecting the condensed water. The thermoelectric module employed in this study was purchased from European Thermodynamics (GM250-49-45-30, see Fig. 4c). The module has a relative large area of 62×62 mm^2 and fabricated using Bi_2Te_3 alloys. Bi_2Te_3 alloys are the best thermoelectric materials for applications around room temperature and readily available commercially [9,10]. A large size module was chosen so that only one module is needed to construct a reasonably sized prototype for this experimental investigation.

The interface between thermoelectric module and heat exchangers were also filled with heat sink compound to ensure effective heat transfer across the contacting surfaces. A micro pump (S/N 14015740 TCS, see Fig. 4d) is used to circulate unevaporated water to gain more heat from the hot side of thermoelectric module.

Two power sources were used to drive the pump and the thermoelectric module. The experimental setup for investigating the developed thermoelectric distillation system is shown in Fig. 5. Specifications of the components used in the experiments with the models and manufacturers are listed in Table 1. Accuracies, ranges and standard uncertainty of measuring instruments are shown in Table 2.

4. Experimental procedure

To evaluate the performance of the system (temperatures, humidity, water productivity and energy consumption), the exper-

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