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Experimental investigation of a solar still equipped with an external heat storage system using phase change materials and heat pipes

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HIGHLIGHTS

- PCM and heat pipes are used for recycling the heat of condensation in a solar still.
- The effect of an external condenser filled with PCM on the water yield is examined.
- The maximum water yield and daily efficiency of 6.555 kg/m^2 day and 50% were obtained.

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ABSTRACT

In this study, a novel idea of storing the latent heat of condensing vapor in solar stills by means of phase change materials (PCMs) as a thermal storage is experimentally investigated. During the daytime, the generated water vapor by the solar energy, is conducted to an external condenser filled with PCM to be condensed. The wasted latent heat is absorbed by PCM and thereby stored. It is worth noting that there is no direct contact between the saline water and the PCM, therefore, the solar energy is not directly stored in the PCM. In the evening, the energy stored in the PCM is transferred as heat to the saline water by heat pipes and enables the desalination process to continue. Several tests were run to investigate the performance of the system. The results revealed that the presence of an external condenser filled with PCM and equipped with heat pipes in a solar still with evacuated tube collectors, makes the desalination process continue after the sunset without causing a decrease in the yield during the daytime. The yield increases by 86% as compared to the yield of the system without PCM and reaches to 6.555 kg/m^2 day with the efficiency of 50%.

1. Introduction

The rapid population growth and industrialization of societies have led to a disequilibrium between the supply and demand of the fresh water [1]. Desalination of the saline seawater is an efficient technique for fulfilling the demand for fresh water. From past times several techniques have been innovated for desalination. Currently, the most prominent processes for desalination are reverse osmosis [2], membrane distillation [3], multistage desalination [4], multiple effect distillation [5], and electrodialysis [6], which rely on fossil fuels. Contamination of the environment by fossil fuels and engagement of the whole world with the energy crisis underscore the necessity for using renewable energy sources in various fields such as desalination. Solar stills, which have two features of being environmentally-friendly and using the sun as a free and available source of energy, are effective systems for desalination especially in remote areas [7]. The basis of the operation of all solar stills is the absorption of solar energy by the saline water, its evaporation and then its distillation and collection as fresh water.

The main disadvantage of solar stills is their low yield as compared to other desalination systems. Therefore, several studies have been conducted to enhance the performance of these systems. An exhaustive review of the studies conducted to increase water yield and efficiency in solar stills is given in [8,9]. Different studies show that increase in the average water temperature, and as a result, increase in the yield of solar stills is possible through addition of solar collectors to these systems [10,11]. Evacuated tube collectors have the characteristic of sun tracking as a result of their cylindrical structure. Furthermore, they have lower heat loss due to the vacuum between the two glass walls, and as a result, have higher performances in comparison with the flat-plate collectors. In these evacuated tubes, either water is directly injected inside the collector or the thermosiphon heat pipe is used to transfer the heat absorbed from the sun to the outside [12]. To increase the efficiency of the solar still, Singh et al. [13] studied a model of a solar still equipped with the evacuated tubes in which the water was directly present inside the collector. They calculated the maximum yield and

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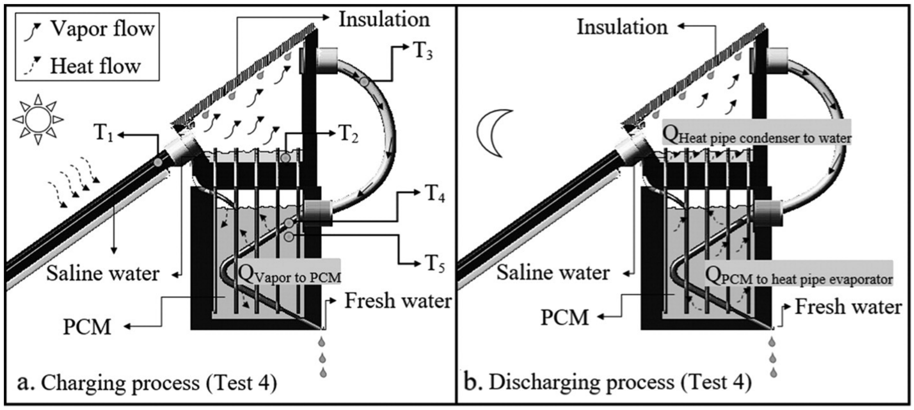

Fig. 1. Schematic of the processes in the system with external condenser containing PCM and heat pipes (test 4), (a) charging process (b) discharging process.

efficiency as 3.8 kg/m^2 and 33%. Jahangiri Mamouri et al. [14] experimentally investigated the performance of a solar still with evacuated tubes and used the heat pipe for the transfer of the heat absorbed from the collector interior to the water basin. The maximum efficiency and hourly yield of 22.9% and 1.02 kg/m^2 h were obtained. Recently, Jafari Mosleh et al. [15] have reached the maximum efficiency of 65.2% by using the evacuated tube and sun tracking system together in a solar still.

One of the disadvantages of solar stills is the waste of latent heat of condensation from the upper glass to the environment [16,17]. For this purpose, several studies are conducted to reduce such wastes. Madhlopa and Johnstone [18] numerically evaluated the performance of a solar still with a three-stage external condenser. They prevented the waste of the heat released from distillation on each stage of the condenser by transferring it to the upper water basin, and enhanced the performance of the system up to 62% in comparison to a simple solar still. Monowe et al. [19] theoretically investigated the effect of the presence of a fan inside the evaporation chamber used for transferring the vapor generated to an external condenser to transfer the heat inside it to a secondary stream. The heat stored by the secondary stream in the heat exchanger has the capability to be used for domestic consumption or for system performance in case no sunshine exists. The efficiency of the system can increase up to 77% and 85% in each case. Karimi Estahbanati et al. [20] examined the performance of a multi-effect solar still and concluded that the increase in yield is in conjunction with the increase in the number of stages in the continuous mode. Recently, Shafii et al. [21] reached the efficiency of 52% by preventing the waste of latent heat of distillation and its recycling by thermoelectric modules which results in the generation of electricity.

Since the solar stills produce water only during the daytime, several studies have been conducted to store energy during the daytime and using it to produce water at night. Part of the heat can be stored as sensible heat in Jute cloth [22], sand [23], charcoal particle [24], and quartzite rock [25]. These materials are located inside the water basin as energy absorbers, and bring about absorption of a portion of the solar energy during the daytime and restore it to the water at night. However, they did not lead to a significant increase in the yield. On the contrary, the latent heat storage systems boast advantages in comparison with sensible heat storage systems such as having higher stored energy density and also storage of the latent heat at the roughly constant phase change temperature [26]. El-Sebaii et al. [27] mathematically modeled the performance of a single slope-single basin solar still by placing phase change materials beneath the water basin to prevent heat waste from the lower section of the basin. In the system they studied, a portion of the energy absorbed by the basin water, melts down the phase change material, and as a result, a considerable amount of the heat is stored in the phase change material instead of being wasted. In the evening, by the decline in the system temperature, the phase change material freezes and the heat released from it is transferred to water. Consequently, the desalination process continues until a few hours after the sunshine. Their results revealed that by storing heat inside the phase change material, the amount of water produced in one day

Table 1
Details of the dimensions and sizes of the equipment used.

	Inner diameter = 4.7 cm
	Outer diameter = 5.8 cm
	Length = 180 cm
Evacuated Tubes	Inclination Angle = 35.5
Water Basin	Area = 20 cm * 20 cm
	Wall thickness = 1 mm
	Insulation = Fiber glass with 3 cm thickness
PCM	Paraffin wax [26]
	Container dimensions = 25 cm * 25 cm * 35 cm
	Insulation = Fiber glass with 5 cm thickness
Heat Pipes	Copper tube, diameter of 1 cm
	Length = 40 cm (Evaporator = 30 cm, Condenser = 2 cm)
	Working fluid = Acetone
	Filling ratio = 15%

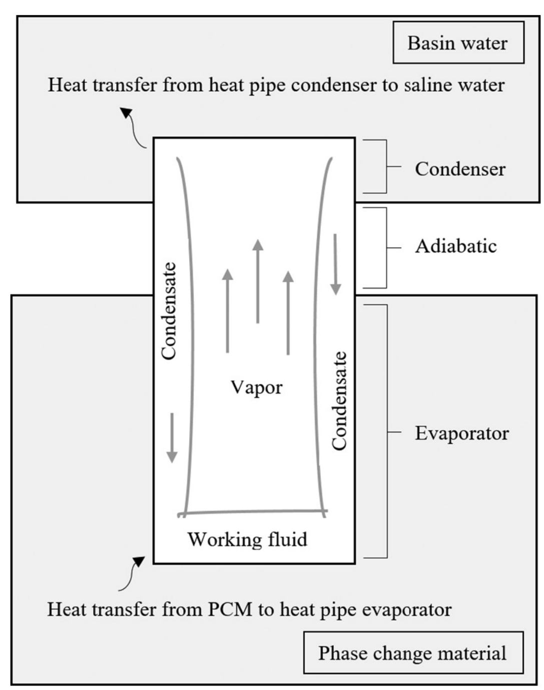

Fig. 2. Schematic of the operation of the thermosiphon heat pipe.