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SOLAR VACUUM TUBE INTEGRATED SEAWATER DISTILLATION - AN EXPERIMENTAL STUDY

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Abstract. *The subject of this study is the seawater distillation process enhancement through integration of the solar vacuum tube into the system. Positive effects on the rate of distillated freshwater achieved by means of the enhanced system have been investigated experimentally. Experiments were done in the Turkish city of Samsun in the Black Sea region. A distillation pond setup having the volume of 0.015m^3 and a water surface area of 0.24m^2 was constructed. The distillation pond is covered with a condensation glass and also equipped with a 0.15m solar vacuum tube that is inclined at an angle of 30^o to the ground, a feed water tank connected with a ball cock, and distillated fresh water tank. Experimental results have shown that the rate of distilled fresh water was enhanced for about 62.5% by integrating the solar vacuum tube and the natural distillation pond. Isolation of the condensation glass not only prevents the light transmission to the pond but also heat loss from the pond; hence the rate of the distillated fresh water is increased for about 137.5% due to the natural distillation.*

Key Words: *Solar Distillation, Solar Vacuum Tube, Solar Pond, Seawater*

1. INTRODUCTION

Useable water sources have been depleting rapidly by population growth, increased demands and industrial development. Most of the countries, including the United Arab Emirates, Kuwait, Libya, Japan, Qatar, Spain, Italy, Iran, suffer from the lack of fresh water sources; they try to solve this problem by seawater distillation and other alternative methods. A number of studies have been conducted with the similar aim of determining a highly efficient, economical and high rate fresh water distillation process. Suarez et al. [1] investigated solar-powered thermal desalination. They found that the heat loss reduction

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throughout the system would yield higher water fluxes, thus pointing to the need to improve the system efficiency. Gonzalez et al. [2] contributed both in the modeling issue, proposing and validating a solar field linear model, and applying an economic optimal control paradigm to solar seawater desalination plants. Gray et al. [3] discussed three alternative desalination technologies, namely, membrane distillation, forward osmosis, and capacitive deionization. Li et al. [4] reviewed the current solar desalination research activities, discussed the solar-assisted desalination processes and a variety of possible combinations. Aybar [5] investigated theoretically an inclined solar water distillation system. Khawaji et al. [6] considered the current status, practices, and advances of the seawater desalination technologies. Lamei et al. [7] compared the cost of seawater desalination by different solar energy technologies. Sampathkumar et al. [8] provided a detailed review of different studies on the active solar distillation system. Wu et al. [9] investigated experimentally a new multi-effect solar desalination system that was based on the process of humidification/ dehumidification. Sebaii and Bialy [10] reviewed different designs of solar stills that are double, triple and multi-effect solar stills, vertical stills, tubular type solar stills, finned and corrugated stills, and stepped type solar stills. Kalogirou [11] discussed various systems that use renewable energy sources for desalination. Aybar et al. [12] studied experimentally a solar water distillation system under the actual environmental conditions. They concluded that the fresh water distillation rate increased about two to three times when wicks were used instead of a bare plate. Sampathkumar and Senthilkumar [13] studied the effective utilization of the solar water heater for solar still productivity enhancement that operates as a hybrid system. Can et al. [14] investigated technically and economically different methods to desalinate seawater in order to obtain, in this way, potable and usable water. Aydın and Ardalı [15] studied technologies for obtaining fresh water. Ketrez et al. [16] discussed the seawater distillation by solar energy. Salim et al. [17] compared three units of the solar water distillation setup which are passive solar still, passive solar still coupled with the collector, and solar still coupled with the collector supported by the copper tube to realize the latent heat. They concluded that the solar collector coupled system productivity is for about 42% higher than the passive solar still. Rajesh and Bharath [18] compared the productivity performance of the seawater distillation by a single basin still and a coupled still with the solar collector. Their study showed that the single basin still productivity enhanced for about 40% upon its coupling with the solar collector. Shabibi and Tahat [19] investigated experimentally the thermal performance of the conventional solar water still with an enhanced solar heating system. It is concluded that the fresh water yielded enhancement of about 50% by the system coupled with the solar preheater. Panchal [20] searched a double basin solar still coupled with evacuated tubes. It was found that the distillate output increased for about 56% by adding vacuum tubes and for 65% by adding vacuum tubes and black granite gravel in the double basin solar still. Rehim and Lasheen [21] presented two modifications for the solar desalination systems. They concluded that the modified solar desalination system efficiency was increased.

2. THEORETICAL BACKGROUND

The energy balance of the desalination process is given by the following equation:

$$m_{sw}c_{sw}\left(\frac{dT_{sw}}{dt}\right) = Ia_{sw}A_{sw} + Q_{c(g-sw)} - Q_{c(g-e)} + Q_{u(vt)} \tag{1}$$

where m_{sw} is the mass of seawater, c_{sw} is the specific heat of seawater, T_{sw} is the temperature of seawater, I is the radiative flux density, a_{sw} is the absorptivity of seawater, A_{sw} is the surface area, $Q_{c(g-sw)}$ is the convective heat transfer from cover glass to seawater, $Q_{c(g-e)}$ is the convective heat transfer from cover glass to environment and $Q_{u(vt)}$ is the useful heat by vacuum tube.

Convectional heat transfer between condensation glass and seawater $Q_{c(g-sw)}$ is estimated as follows [22]:

$$Q_{c(g-sw)} = h_{(g-sw)}A_{sw}\Delta T_{(g-sw)} \tag{2}$$

where $h_{(g-sw)}$ represents the convectional heat transfer coefficient [22]:

$$h_{(g-sw)} = 0.884(\Delta T_{(g-sw)} + (p_{sw} - p_g)(T_{sw})/(268.9\cdot 10^3 - p_{sw}))^{\frac{1}{3}} \tag{3}$$

with p denoting the partial pressure.

Convectional heat transfer from the condensation glass to environment ($Q_{c(g-sw)}$) is estimated using the following equations [22]:

$$Q_{c(g-e)} = h_{(g-e)}A_g\Delta T_{(g-e)} \tag{4}$$

$$h_{(g-e)} = 2.8 + 3U \tag{5}$$

where $h_{(g-e)}$ is the convectional heat transfer coefficient, A_g is the condensation glass surface area and U is the wind velocity.

Solar vacuum tube useful energy input to the pond is denoted as $Q_{u(vt)}$, and can be given as [23]:

$$Q_{u(vt)} = a_{vt}I_{vt}A_{vt} - (E_{rr} + Q_e) - Q_s \tag{6}$$

where a_{vt} is the absorptivity of vacuum tube, I_{vt} is the vacuum tube insolation, A_{vt} is the vacuum tube window area, E_{rr} is the reradiated energy flux, Q_e is the convection energy to environment from vacuum tube and, Q_s is the energy stored by vacuum tube body.

In this study, the process of obtaining freshwater by distilling seawater in a solar pond coupled with a solar vacuum tube has been investigated. Natural water circulation in the solar vacuum tube is the advantage that enables a higher rate of distilled freshwater without any external circulation energy input. The experimental study has been conducted considering the economic and environmental advantages of this process.

3. EXPERIMENTAL SETUP

In this experimental study, a pond setup is constructed with 0.24 m^2 water surface area, and 0.015m^3 water capacity. The constructed pond is equipped with a 0.15 m solar vacuum tube. Water circulation in the solar vacuum tubes occurs naturally and so it does not require any external circulation energy input into the system. The vacuum tube is inclined at an angle of 30^o for optimal solar light absorption. The solar pond internal surfaces are painted with black dye because of its high absorption coefficient (about 0.96). The solar pond is filled with seawater up to the level of about 0.05m. The feed water tank is attached to the pond with a ball cock to maintain constant water level in the pond. Firstly, the water heated by solar energy evaporates; a high temperature steam meets low temperature condensation glass and condenses. Condensed water droplets on the condensation glass come together and drip to the fresh water separation channel. Distillated water in the channel flows in a pipe line and collects in the fresh water storage tank. Water and condensation glass temperature is measured by T-type thermocouple. Potential difference between thermocouple ends is read by Voltcraft M3850 model multimeter. Solar radiation is measured by Cem DT-1307 model solarimeter. The experimental setup is illustrated in Fig. 1.

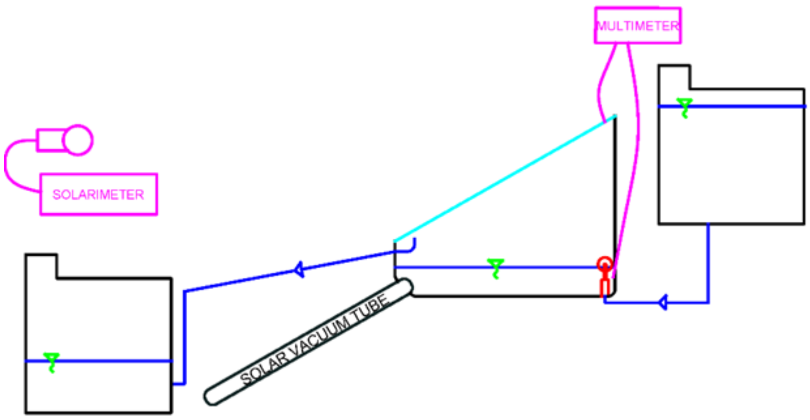

Fig. 1 Experimental setup

Distillation performance is investigated for three different setup configurations. Firstly, the solar vacuum tube is isolated and the water is exposed to solar radiation from the condensation glass. Secondly, the solar vacuum tube is uncovered and the solar penetration to the water is allowed from the tube and condensation glass. Lastly, the condensation glass is isolated and solar radiation allowed only from the solar vacuum tube. Except for the aforementioned surfaces, all other surfaces of the setup are isolated to avoid heat losses. Each configuration is studied in three consecutive cloudless spring days. Measurements were taken every 15 minutes between 10:00 am to 4:30 pm and recorded.

4. Results and Discussion

The obtained measurement data are evaluated and the relation between the thermal parameters and the distilled fresh water rate is assessed in this section.

Fig. 2 illustrates the temperature variation of the condensation glass for different system configurations and environmental effects with respect to the time. Solar radiative density is also given. Isolation of condensation glass prevents heat loss from the glass. Increase in the water temperature by solar energy from the vacuum tube increases the heat transfer from hot water to glass. The glass temperature fluctuates due to the variation of the flux density and heat loss from the glass surface for the non-isolated glass and vacuum tube configuration. The decrease in the temperature in the period of time between 50-100 min could be related to the low environmental temperature. The high temperature difference between the glass and the environment causes a higher heat loss from the glass than the supplied heat by solar radiation.

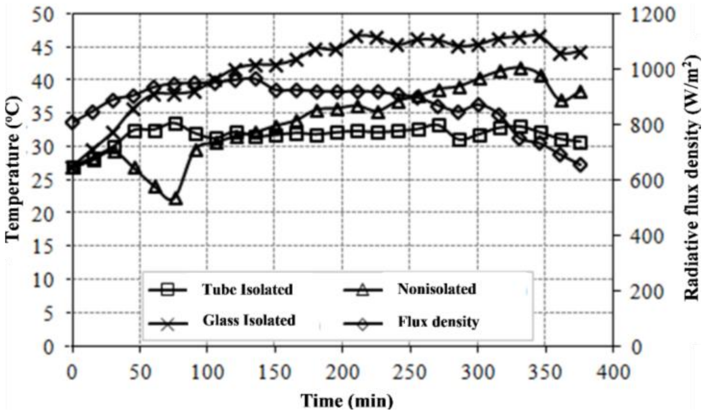

Fig. 2 Solar radiative flux density and condensation glass temperature

Fig. 3 illustrates the distillation pond water temperature and solar radiative heat flux. It shows that the transmitted natural solar radiation and the enforced radiation by the solar vacuum tube tend to increase the overall water temperature. Similar results are reported in [20] emphasizing that the integrated vacuum tube increases the water temperature compared to the single basin solar still. However, the low environmental temperature causes a higher heat loss *via* the glass surface than the heat supplied by solar radiation in the first hours of the experiment (between 50-100 min) and so there is a sudden water temperature decrease. The configuration with the isolated tube, i.e. with the water heating only by the natural solar radiation *via* the condensation glass, slightly increases the water temperature. The most efficient heating of water is provided by the isolation of the condensation glass so that the heat loss from the system is reduced thus causing a notable increase in the water temperature.

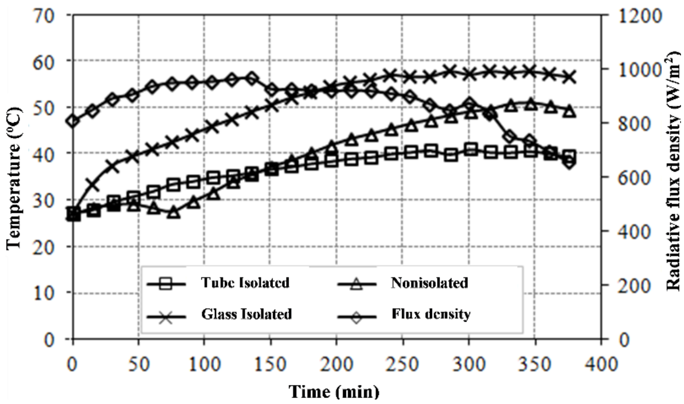

Fig. 3 Solar radiative heat flux and solar pond water temperature

Fig. 4 shows the condensed fresh water quantities obtained by the three different experimental configurations. The quantity of condensed fresh water varies depending on the water temperature, glass temperature and the heat transferred to the water. About 160 ml of fresh water was obtained in the configuration that allowed solar radiation from the condensation glass. Low radiation heat transfer and a high heat loss *via* the condensation glass cause a low temperature difference (about 5^{o}C) between the water and the condensation glass. Low energy transfer means the low vaporization. Likewise, a low temperature difference leads to a low condensation rate. The non-isolated condensation glass and the vacuum tube cause a higher temperature difference and a greater heat loss *via* the glass surface. Also, the low temperature difference (about 8^{o}C) between the water and the condensation glass resulted in 260 ml of distilled fresh water. The highest quantity of fresh water was obtained in the case that combined the isolated condensation glass and the non-isolated solar vacuum tube. The isolated condensation glass means a negligible amount of heat loss *via* the glass to the environment and the highest amount of the heat gained by the system. Additionally, the highest temperature difference (about 12^{o}C) between the condensation glass and the pond water led to the highest quantity of condensed fresh water of 380 ml.

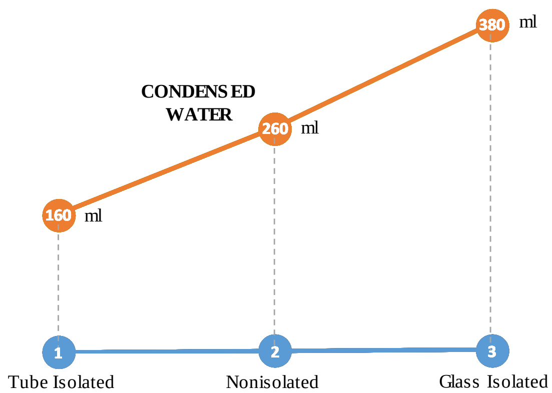

Fig. 4 Condensed fresh water quantity

5. CONCLUSION AND OUTLOOK

In this study, the advantages of seawater distillation conducted on a solar pond with an integrated solar vacuum tube have been investigated experimentally. The process can be evaluated as environment friendly, economical, and efficient. The solar vacuum tube increases the gained heat energy and the quantity of distillated water. The tube has a natural fluid circulation and, hence no external circulation energy input is required. Additionally, it has a long service life and a wide range of temperature operability. The investigated distillation process is applicable to the districts that generally suffer from the lack of energy except for solar one. The fresh water distillation rate was increased by 62.5% through integration of the solar vacuum tube into the system. This result was even further enhanced up to 137.5% by the elimination of heat loss from the condensation glass. The problem of an efficient high rate of the fresh water production by alternative methods in order to solve the problem of the people living in the areas with scarce water sources has been investigated by other researchers in the field. The solar pond coupled with a vacuum tube configuration was studied in order to contribute to the studies in the field and to focus on more environment friendly, efficient, and mobile configurations which are independent of exhaustible energy.

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