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Simple Solar Still Using Solar Energy and Compost Heat for Family Use

Shotaro KIKUCHI*[1], Hiromichi TOYODA[2], Akane TAKAMI[1],
Sawahiko SHIMADA[2], Makoto OOBA[3] and Tetsuo SEKIYAMA[4],

Abstract: In this study, we conducted vapor distillation experiments at National Crops Resources Research Institute and Tokyo University of Agriculture (TUA). The objectives of this study were to boost the performance of distillation by using compost heat, and to activate natural convection in a solar still. The compost was made from cow dung and rice straw in a box. As a result of the measurement of the compost temperature distribution the effective depth of the compost, as a source of heat underneath the still, was 20 cm from the surface. The surface temperature of the solar still cover, made of polyethylene sheets, and the amount of distillation at experimental field in Uganda and an environmentally controlled room at TUA. According to the field experiment in Uganda, distilled water was obtained mostly from the western side in the morning, and the eastern side in the afternoon. Experiment in the environmentally controlled room revealed that increases in the temperature variance of the solar still cover tended to increase the amount of distillation and the Ra number. We assumed that there would be a close relationship between the temperature variance of the solar still cover, natural convention and distillation.

Key Words: Compost heat, Distilled water, Natural convection, Solar energy, Solar still

1. Introduction

According to UNICEF (2010), 884 million people in the World still don't have access to safe drinking water. Most of these people are living in Sub-Saharan Africa. Moreover, this number is expected to increase in event of natural disasters. In this study, we developed a simple solar still which can make clear water and be managed by a household. We attempted to estimate the performance of the solar still and investigated distillation by compost heat and natural convection in the still in order to increase the amount of distilled water.

2. System Description

2.1. Construction

The solar still basin had a basal area 1 × 1 m, and it was made of plywood (**Fig. 1**). A black mulch plastic film was laid on the bottom, and the cover was made of PVC transparent film of 0.05 mm thickness. It was tilted at an angle of 60 degrees to the horizontal surface. The compost was set under the basin. The well water in the basin was heated and evaporated by solar energy and compost heat, and the evaporated water was condensed near the cover. Finally, it was collected and analyzed. We performed the distillation experiments and distilled water analysis at National Crops Resources Research Institute from Aug. 2010 to Sep. 2010 and inside the environmentally controlled room at Tokyo University of Agriculture (TUA) in Apr. 2010.

Fig. 1. Developed solar still.

2.2. Practicability

The still material was purchased locally in Ethiopia in 2009 and cost approximately $4.00 U.S., which is 1% of the cost of a commercial solar still.

Distilled water analysis was performed by electric conduction (EC), pH and bacteria counting, and by comparing distilled water with well water. As a result, EC decreased from 0.175 ms cm^{-1} to 0.013 ms cm^{-1}. The bacteria counting was conducted using an agar medium. A 0.05 ml sample of which well water and distilled water diluted 200 times, was then dropped in to an agar medium. The colony number of

Corresponding Author: 65100001@nodai.co.jp
1-1-1, Sakuragaoka, Setagaya, Tokyo, 156-8502 Japan
1) Graduate School of Agriculture, Tokyo University of Agriculture
2) Faculty of Regional Science, Tokyo University of Agriculture
3) Asian Environment Research Group, National Institute for Environmental Studies, Japan
4) Ibaraki Agricultural Academy

bacteria and *E. coli* decreased from 33 to 3 and 34 to 0, respectively. However, pH did not show any significant difference.

2.3. Mathematical model

Distillation efficiency is adopted as an index of energy efficiency of solar still in this study. Distillation efficiency (E_{Dis}) is given by

$$EDis = le / Aw (rn+qe -hw) \qquad (1)$$

where l is latent heat of vaporization (J g^{-1}), e is evaporation rate (g s^{-1}), A_w is area of basin (m^2), rn is solar radiation of passed the film(W m^{-2}), q_e is compost heat input per basin unit area (W m^{-2}), h_w is sensible heat per unit area from basin (W m^{-2}).

In this study, the Rayleigh number (R_a) was used for analyzing temperature distribution and natural convection in the still. The R_a number is dimensionless number associated with buoyancy driven flow. The R_a number is defined as:

$$R_a = \frac{g\beta(T_w - T_g)}{v \cdot \alpha} L^3 \qquad (2)$$

where g is gravitational acceleration (m sec^{-2}), β is coefficient of volume expansion (K^{-1}), T_w is temperature of water surface (K), T_g is air temperature near the cover (K), v is kinematic viscosity coefficient (m^2 sec^{-2}), α is thermal diffusivity (m^2 sec^{-2}), L is distance between water surface and cover (m). Omari (2005) explains the relationship between the amount of distilled water and the R_a number from numerical simulation. He also states the R_a number increases with the accumulated amount of distilled water. Therefore, the temperature difference between the water surface at the basin and cover at the upper sides may play an important role in producing distilled water in terms of activating convection inside of the still.

3. Materials and Methods

3.1. Natural convention

Figure 2 shows a schematic diagram of the solar still. Thermocouples recorded temperatures at various points in the still (four directions on the covers and air temperature inside of 1 cm, and 25 and 75 cm above water surface at the east side). An experiment in the environmentally controlled room was conducted to monitor the relative humidity at the center of the still, where the air was affected by heat aggregation. An electric heat cable (100 V, 125 W) and two lamps (500 W at an angle of 45 degrees) were used to illuminate and heat the basin water instead of solar radiation.

3.2. Compost heat

Compost produced from cow dung (500 kg) and rice straw (100 kg) was set inside wooden box (1×1×0.7 m). The compost temperature was measured at intervals of 10 cm from the top surface to the bottom by the thermocouples (Fig. 2).

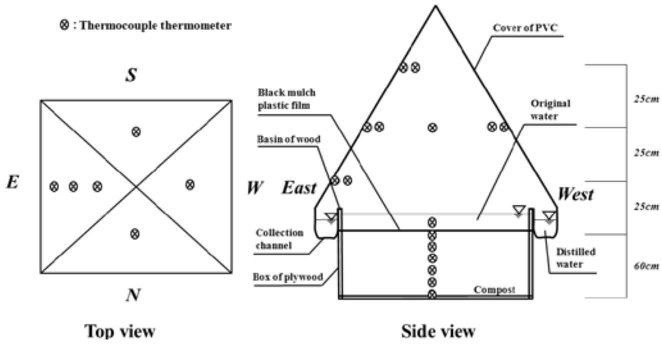
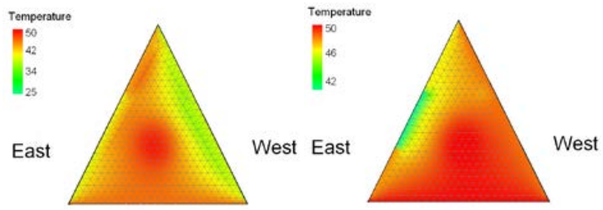


Fig. 2. Schematic diagram of the experiment.



(a) 11:00 **(b) 14:00**

Fig. 3. Temperature distribution of solar still in 5th of September.

4. Results and Discussion

4.1. Natural convection

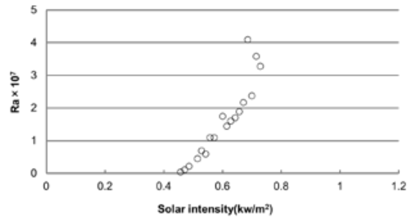
4.1.1. Temperature distribution of solar still in Uganda

All data was recorded between 26 August to 17 September, 2010. Temperature distribution in the still at 11:00 and 14:00 in 5 Sep. are shown in **Figure 3**. This diagram was derived by interpolating 10 measuring points (Fig. 2) using FEM software (XFEM). The temperature at the center of the still at 11:00 was the highest temperature of the ten measuring points. On the other hand, temperature at every measuring point in the still at 14:00 recorded maximum and the surface of the basin water was the highest point.

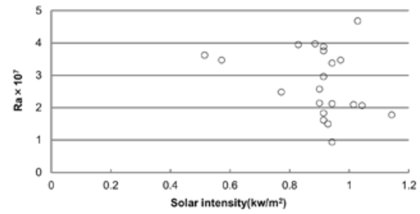
In the environmentally controlled room, the humidity inside the still remained of 100% when the still was heated by the heating cable, whereas it decreased to 80% when heated by heating lamp. Therefore solar radiation is assumed to have two heating effects, namely; basin water heating and air heating inside the still. Also temperature differences have been observed around the cover's four sides. These temperature differences are assumed to reflect the ability to produce distilled water from each cover side (**Table 1**). The relatively cool cover on the opposite side of the solar azimuth was found to be the most appropriate zone to produce distilled water. The amounts of distilled water from the four direction sides from 8:00 to 13:00 were nearly equal. However, the cover is eastern side from 13:00 to 18:00 produced more than twice the

Table 1. Amount of distilled water of north south east and west side.

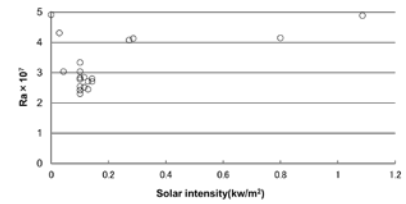
3/9/2010	Water temperature (℃)	Solar intensity (W/m^2)	Distilled water of each four direction film surface (ml)				
			East	West	South	North	SUM
8:00 to 13:00	39.3	677	166	195	147	120	628
13:00 to 18:00	40.3	281	228	103	52	73	456



(a)Variation of R_a between 8:00 to 11:00



(b) Variation of R_a between 11:00 to 13:00



(c) Variation of R_a between 14:00 to 16:00

Fig. 4. Relationships between R_a number and solar intensity.

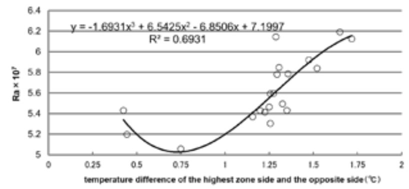
amount of distilled water compared with the other sides during each experiment.

4.1.2. R_a number

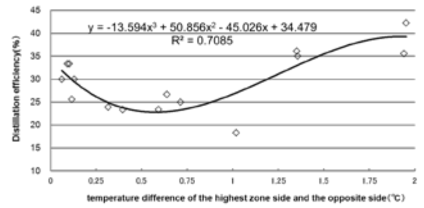
A relationship between the Rayleigh (R_a) number and solar intensity is shown in **Figure 4**. The measurements were taken three times a day, morning, noon and afternoon (8:00 to 11:00, 11:00 to 13:00 and 14:00 to 17:00). The R_a number increased as solar intensity rose in the morning due to the rise in basin water temperature. However, the R_a number decreased from noon because the temperatures at all sides of the cover were equally high due to the solar radiation from the zenith. The R_a number tended to increase in the afternoon, but this was not as remarkable during the morning period. A strong correlation was found between the R_a number and solar radiation especially during the morning.

4.1.3. Surface temperature difference between east and west sides

This experiment was undertaken to investigate for the relationship between the temperature at the cover's highest zone side and its opposite side (the lowest side). **Figure 5** shows the Ra number and distillation efficiency visaris the temperature difference. The electric heat cable was used in



(a) R_a number



(b) Distillation efficiency

Fig. 5. *Ra* number and distillation efficiency within temperature difference between the highest zone side and the opposite side.

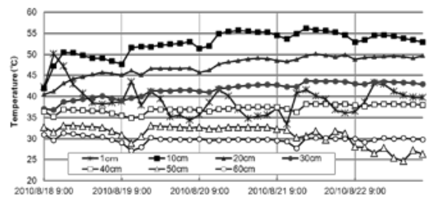


Fig. 6. Temperature of sealing compost.

the environmentally controlled room for heating the water in the basin. As a result, both the R_a number and distillation tended to increase from around 0.75°C. The temperature difference is explained by the close relationship between natural convention and distillation.

4.2. Compost heat

4.2.1. Temperature distribution of compost

The temperature distribution of sealed compost from 1 cm to 60 cm depth is shown in **Figure 6**. The temperature was monitored from 18 to 22 August 2010. A box was filled with compost and covered with a plastic sheet. As a result, the temperature at 1 cm depth varied due to air temperature variations, and deeper part of the compost temperature (1- 60 cm) tended to decrease with the depth increased inside the compost. From the compost depth between 10 cm to 30 cm,

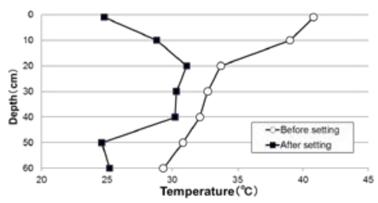
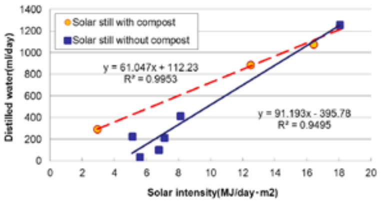
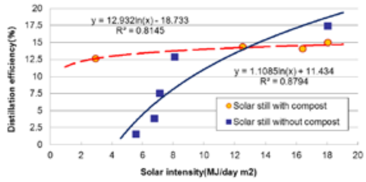


Fig. 7. Compost temperature after the solar still set up.



(a)Distilled water



(b) Distillation efficiency

Fig. 8. Distillation efficiency and distilled water for solar still with and without compost.

Table 2. Distilled water and distillation efficiency.

Compost	Date	Solar intensity	Distilled water	Efficiency	Place
Nonuse	23/10/2009	5.6MJ/day	34ml	1.54%	Tokyo
Use	26/8/2010	2.9MJ/day	296ml	14.5%	Uganda
Nonuse	3/9/2010	18.0MJ/day	1259ml	17.4%	Uganda
Use	17/9/2010	18.0MJ/day	1243ml	15.0%	Uganda

temperature increased while from 40 cm to 60 cm it didn't change during the 5 day measurement period. The compost near the bottom had a low temperature, because of the weak fermentation caused by a lack of oxygen.

Figure 7 shows the temperature of the compost, fermented for 5 days, both one day before and one day after it was installed underneath the still. As a result, from 1 to 20 cm, temperature decreased greatly, while from 20 cm to 60 cm the decrease was smaller. Therefore, the valid range of the depth as a source of heat is from 1 to 20 cm.

The heat transfer value from the compost to the basin was calculated using the following equation.

$$Q = c\,m\,(T_1 - T_2) \qquad (3)$$

Where Q is heat value (J), c is specific heat (J kg^{-1} K^{-1}), m is compost mass (kg), T1 - T2 is temperature difference. c was referred from Ahn (2009). As a result, the heat transfer value was calculated at 2.85 MJ, and 296 m/s of distilled water was produced over 18 hour. The amount of solar radiation was 2.9 MJ during the experiment.

4.2.2. Quantity of compost and effect of compost heat

Heat transfer value from the compost was measured in order to investigate the heat value difference by compost thickness. This compost was put in the box of 1×1×0.1 m. The average heat transfer value of 10 cm thick and 60 cm thick were calculated for 2 days. As a result, they were calculated to be 2.7 MJ day^{-1} and 2.9 MJ day^{-1} for 10 cm and 60 cm, respectively. A comparison of the solar still's distillation efficiency (with and without compost) is shown in **Figure 8** with measuring date shown in **Table 2**. The experimental data from Tokyo was quoted from Hasegawa (2010). The still without compost showed higher distillation efficiency than the still with compost when solar intensity was over 12 MJ day^{-1}. One reason for this may be the basin water became hotter than the compost temperature at noon. However, the still's distillation efficiency with compost was stable at over 12% and was able to produce more distilled water (over 200 ml) than the still without compost when solar intensity was less than 12 MJ day^{-1}.

5. Conclusion

Based on the results obtained from the experiments, the followings can be concluded.

1. Solar radiation has two effects it heats basin water and the air inside solar stills. The still's humidity (heated by a lamp) was about 80% in the environmentally controlled room.
2. Distilled water can be produced when the cold cover condition was induced at the opposite side of the solar azimuth within the solar still. The eastern cover in the afternoon produced twice the amount of distilled water compared with of other directions in Uganda.
3. The R_a number increases according to solar intensity rises in the morning and afternoon. However, the R_a number tends to decrease at noon.
4. The R_a number and distillation efficiency tend to increase with temperature differences of the two sides of the solar still cover.
5. The effective depth of the compost as a source of heat underneath the still was 20 cm from the surface.
6. The distillation efficiency of the solar still with compost was stable at over 12%. Moreover, the performance of the solar still with compost was found out to be more efficient in producing 200 ml more distilled water than the one without compost.

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