Performance of the solar distillation pyramid type to desalinate seawater into freshwater

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Abstract. The solution of drinking water for coastal communities is to desalinate seawater into freshwater through implementation of the solar distillation pyramid type's technology. This technology utilizes solar thermal energy (greenhouse effect) to speed up the condensation process by watering the roof. This research aimed to determine the solar desalination pyramid type's performance and determine the effect of flushing treatment on solar distillation. Seawater about 4000 mL was put into a seawater container of the solar distillation pyramid type. The heating process would be carried out by sunlight, which causes seawater to be evaporated on the roof. Flushing treatment was given on the wall to accelerate the condensation process, so the temperature differences between the ambient and the solar distillation pyramid were obtained. The water vapor will turn into water and drip on the glass room walls, thus stream down through waterways and reservoirs. The research results that the energy efficiency of the solar distillation about 52.93% and obtains fresh water about 2317 mL for three days of observation. Freshwater quality from the desalination process fulfills the Indonesian Standard (SNI) 01-3553-2021 of drinking water, with a salinity of 0%, pH of 6.5, EC of 8 μS/cm, and TDS of 9 mg/L. The efficiency of solar distillation pyramid type is about 52.93%. This technology is a widely feasible solution for coastal communities because it is straightforward to construct and achieves higher reliability and cost minimization.

1. Introduction
Water in the coastal area mostly consist of seawater mixed with brackish water. Brackish water is contaminated with NH₃, H₂S, and other chemical which harmful to human health. The acidity level of brackish water higher than the pH level makes it is not worth drinking. Seawater has a high level of salinity (35 g) such as chloride (55%), sodium (31%), sulfate (8%), magnesium (4%), calcium (1%), potassium (1%), and less (about 1%) consist of bicarbonate, bromide, boric acid, sodium, and fluoride [1]. High salinity levels make it impossible to consume seawater directly without going through the processing process. A desalination process must be carried out to separate water from the seawater's salt content for freshwater consumption [2]. Several methods can be used include distillation, osmosis, and electrodialysis [3].

Desalination processes require significant quantities of energy to achieve the separation of salts from seawater. This research provides a solution to produce fresh water by desalination process, distilling
saltwater into freshwater. The conventional method for desalinating seawater is to evaporate seawater and condense the arising vapor being free of salt [3]. In most cases, such desalination plants are designed as multi-stage evaporator plants using fuels as an energy source. This process is the basis for a daily production of several million cubic meters of water [4]. This is highly significant as it is a recurrent cost, which few of the world's water-short areas can afford. People in many other regions of the world have neither the cash nor the oil resources to develop. The increase of desalinated water supply will create a series of problems, the most significant of which are those related to energy consumption and environmental pollution caused by fossil fuels. If desalination is accomplished by conventional technology, it will require substantial quantities of fossil fuels. Given that conventional energy sources are polluting, sources of energy that are not polluting and could be used to drive desalination processes, such as solar energy [5].

Solar energy is a source freely available in nature as renewable energy. The main characteristic is friendly to the environment, not produce harmful effluents. Production of freshwater using desalination technologies driven by renewable energy systems thought to be a viable solution to water scarcity in remote areas characterized by a lack of potable water and conventional energy sources like heat and electricity grid [5]. The solar desalination process offers the advantage of doing practically no ecological damage and creating minimum energy cost. Solar water evaporation plants use collected solar energy for direct heating and evaporation of salty water to gain distilled water [6-9]. In other cases, solar energy has been used to heat seawater and later to inject the warm water into the air to humidify it. The subsequent cooling of the humid air delivers the needed water free of salt [10,11]. In all processes, the salty water is directly heated by the sun [12].

A representative example of direct collection systems is the conventional solar still, which uses the greenhouse effect to evaporate salty water. It consists of a basin, that amount of seawater enclosed in a V-shaped glass envelope. The sun's rays pass through the glass roof and absorb by the blackened bottom of the basin. As the water is heated, its vapor pressure increased. The water vapor is condensed on the roof's underside and runs down into the troughs into the reservoir. The still acts as a heat trap because it is transparent for the incoming sunlight but opaque to the hot water's infrared radiation (greenhouse effect). The roof encloses all of the vapor, prevents losses, and keeps the wind from reaching and cooling the salty water [5].

This research aims to determine the solar desalination pyramid type's performance and determine the effect of flushing treatment on solar distillation. Information from solar still can be utilized to achieve higher reliability and cost minimization. Although renewable energy-powered desalination systems cannot compete with the conventional water production cost, it is applicable in certain areas and likely to become more widely feasible solutions for coastal communities.

2. Materials and Methods

2.1. Materials
The material used in this research is seawater from Batu Bekung Beach, Gajahrejo Village, Gedangan District, Malang Regency. Solar distillation pyramid type made from thick glass of 5 mm, useful for storing heat and transmitting heat from outside into the greenhouse. The container is placed in a glass room as a product of freshwater. A chimney is a place for air circulation to help the condensation process inside. The water channel is a channel for freshwater to flow from the condensation. The output channel connects the gutter water channel to the freshwater container (Figure 1).
2.2. Solar distillation research method
Data were collected for three days at 08.00-17.00 every day; T1 (wall temperature), T2 (ambient temperature), T3 (roof temperature), T4 (chamber temperature), T5 (water temperature), intensity sunlight, humidity, and the freshwater volume. The flushing treatment on the wall was carried out for about 1 minute for every hour. The position of solar distillation pyramid type was in the north side to get more solar energy according to the geographical location of the research in Malang, East Java [13].

Seawater about 4000 mL was put into a basin for purification using solar energy. The sun's rise pass through the glass roof and absorb by the blackened bottom of the basin. As the water is heated, vapor pressure increased. The resultant water vapor is condensed on the roof’s underside and runs down into the troughs, which conduct the distilled water to the reservoir. The still acts as a heat trap because the top is transparent to the incoming sunlight, but it is opaque to the infrared radiation emitted by the hot water (greenhouse effect). The roof encloses all of the vapor, prevents losses, and keeps the wind from reaching and cooling the salty water. Flushing was given on the roof to accelerating the condensation process, so the temperature differences between the ambient and the solar distillation were obtained. The water vapor will turn into water and drip on the glass room walls, thus stream down through waterways and reservoirs.

2.3. Data analysis
a. Internal Heat Transfer
The amount of internal heat transfer can be calculated by equation [14]:

1) The exchange of radiation between water reservoirs using black colored glass with an emissivity of 0.9 and the surface of the distillation equipment:

\[ q_{r,b-g} \times 0.9 (T_b - T_g)^4 \]  (1)

2) The transfer of convection energy from the water reservoir to the surface in the distillation unit is based on Newton's cooling law equation:

\[ q_{c,b-g} = h_{c,b-g} (T_b - T_g) \]  (2)

3) Natural convection because it takes between the surface of the water and the surface of the glass in the distiller so that the equation for the convection heat transfer coefficient is like the equation:

\[ h_{c,b-g} = 0.884 \left[ (T_b - T_g) + \frac{(P_{ab} - P_{bg})}{268.9 \times 10^3 P_{ab}} \right] T_b \]  (3)

4) The partial vapor pressure of water in the air (°C) can be calculated by the equation:

\[ P = 7235 - 431.43 T + 10.76 T^2 \]  (4)
b. External Heat Transfer

1) The transfer of external energy through convection can be calculated using the Newton cooling convection equation:

\[ q_{c,g-a} = h_{c,g-a}(T_g - T_a) \]  

(5)

2) The transfer of external energy through radiation can be calculated by the equation:

\[ q_{r,g-a} = \varepsilon_g \sigma \left( T_g^4 - T_{sky}^4 \right) \]  

(6)

3) The convection heat transfer coefficient from glass to the ambient can be calculated by the equation:

\[ h_{c,ga} = 2.8 + 3.8v \]  

(7)

4) The heat loss from the desalinator to the ambient can be calculated by the equation:

\[ q_L = U_L(T_b - T_a) \]  

(8)

3. Results and Discussion

3.1. Temperature

Figure 2 shows that the value of ambient temperature is influential on glass temperature and water temperature because the glass temperature decreases easily if the ambient temperature also decreases compared to seawater temperature, because seawater is good heat storage. In the observation data for 3 days, the seawater temperature was between 30-52 °C, and the glass temperature (roof) was between 19-38 °C.

![Figure 2. Temperature of solar desalination pyramid type.](image)
The glass temperature is lower than the ambient temperature and seawater temperature because the glass (roof) is sprinkled with water to decrease the temperature. The seawater temperature is higher than the glass (roof) temperature, and the ambient temperature is caused by the greenhouse effect. The higher the temperature, the greater the intensity of the sunlight obtained, and vice versa. The lower the temperature, the sunlight intensity is smaller. In a previous study by Handoko [15], the reception of solar radiation at the earth's surface varies greatly according to place and time, i.e., especially due to differences in latitude and atmospheric conditions, such as clouds. The slope area determined the amount of radiation received, based on the difference of radiation that occurs in a day (from morning to evening) and seasonally (from day to day).

3.2. Relative humidity
The relative humidity is measured every 1 hour at 08.00-17.00 WIB in 3 days, both in the chamber and ambient (Table 1). The chamber humidity is 60-99%, higher than the ambient humidity. The ambient humidity decreases from morning to noonday and increases during the noonday to evening because of wind factors and the sun's heat. The wind factor can affect the temperature if the wind velocity increases. The sun intensity that entering the chamber will be smaller, so the temperature will decrease. It is following Hadi's research [16], chamber humidity is influenced by chamber temperature. The higher the chamber's temperature, the lower the chamber humidity because the water activity in the air is small, and the intensity of sunlight received by the chamber highly. Otherwise, the lower the chamber temperature, the higher the chamber humidity, caused by high water activity in the air and very little sunlight intensity.

3.3. Solar radiation
Solar radiation measurements are carried out every 1 hour at 08.00-17.00 WIB for 3 days. The results of solar radiation carried out for 3 days are as in Figure 3.
Figure 3. Solar radiation in three days of observation.

Figure 3 shows that the highest solar radiation occurs at 11.00 every day. It is related to the sun's angle of incidence, which was form by the sun and the earth's surface. During the day, when the angle is perpendicular, the Earth receives more radiation. It will be different when the angle of sunlight incidence is low, solar radiation is also lower. This phenomenon is due to the earth's movement in an elliptical orbit and from an oblique direction (concerning an elliptical orbit) or its rotational axis, but it is also due to changes in the angle of impact (declination) of sunlight throughout the year. The value of solar radiation is influence by the angle and direction of the sun's fall on the earth's surface [17].

3.4. Effect of flushing water
Solar distillation requires frequent flushing or watering, usually done during the night. Flushing is performed to prevent salt precipitation [18]. Watering on the roof is carried out every 1 hour from 08.00-17.00. The temperature on the greenhouse walls is between 30-50 °C, and after flushing, the temperature becomes about 19-37 °C (Figure 4).

The temperature before flushing has the highest temperature of 41.6 °C at 11.00 AM and decreases after flushing about 32.7 °C. The temperature of the glass after flushing decreases due to forced cooling. It was a change in temperature on the glass wall caused by the water temperature that reduced the glass temperature from high to low due to heat transfer. According to Klara's research [19], the molecules in the hotter part of the gas have higher average energy colliding with low energy molecules, so some of the energy from high energy molecules is transferring to low energy molecules.

Glass material easily absorbs heat and also quickly releases heat. If the weather was cloudy, there would be natural or forced cooling so that the ambient temperature is low, making the glass temperature changes quickly. This condition is advantageous for this solar distillation to obtain freshwater faster and produce a lot of freshwaters. The decrease in temperature on the wall will accelerate the occurrence of condensation. Water vapor will stick to the wall, due to water vapor change to the dew point temperature
will occur [20,21]. Water that flows over the wall will decrease the temperature of seawater and the wall.

3.5. Freshwater production
The most accumulated freshwater production occurred on the first day producing 844 ml of water, then followed by the second and third day, i.e. 777.5 ml and 695.5 ml (Table 2). It is because solar radiation during the first day is greater than the second and third days. Cloudy conditions in an area affect the intensity of sunlight received. The water flow production decreases on the second day from 12.00 to 13.00, due to the decreasing of solar radiation and cloudy. The total production of freshwater for three days is about 2317 mL (57.93%). Although the yield of solar stills is low, the use of solar distillation is proving economically viable for small water quantities required, and the cost of installation of pipework and other equipment required to supply an arid area with naturally produced freshwater is high [5].

Freshwater quality from the desalination process fulfills SNI 01-3553-20215 of drinking water (Table 3), with the salinity of 0%, pH of 6.5, EC of 8 μS/cm, and TDS of 9 mg/L. Solar distillation can be used as desalination to attain self-reliance and ensure a regular supply of freshwater, where salty water is the only water available. It is feasible if water pipelines were uneconomical, and truck delivery was unreliable or expensive.

| Table 2. Production of freshwater. |
|-----------------------------------|
| Time (hour) | Production of freshwater (mL) |
| Day 1 | Day 2 | Day 3 |
| 08.00 | 0 | 0 | 0 |
| 09.00 | 39.00 | 50.00 | 24 |
| 10.00 | 68.00 | 93.50 | 67 |
| 11.00 | 119.00 | 115.00 | 99 |
| 12.00 | 135.00 | 150.00 | 108.5 |
| 13.00 | 138.00 | 88.50 | 111 |
| 14.00 | 124.00 | 123.00 | 95 |
| 15.00 | 109.00 | 84.00 | 83 |
| 16.00 | 73.00 | 41.00 | 46 |
| 17.00 | 39.00 | 32.50 | 26 |
| Total | 844 | 777.5 | 659.5 |

| Table 3. Freshwater quality in the solar distillation. |
|-----------------------------------------------|
| Parameter | Unit | Water sample seawater | Fresh water | SNI | Distilled water |
|-----|------|-----------------|---------|-----|----------------|
| Salinity | % | 33 | 0 | 0.05-0.1 | 0 |
| Acidity (pH) | - | 6.1 | 6.5 | 6.0-8.5 | 7 |
| Electrical Conductivity (EC) | μS/cm | 5054 | 8 | 20-12500 | 0.5-3 |
| Total Dissolved Solid (TDS) | mg/L | 2590 | 9 | < 1000 | 10 |

3.6. Energy in the solar distillation
Energy balance consists of internal energy and external energy (Table 4). In a desalination process, the intensity of sunlight hitting the tool occurs light reflection on the glass, absorption on the glass, and light transmitted to the glass. Only a fraction of the incident solar radiation received on the glass roof that
reflected and absorbed by the glass surface material, thus mostly transmitted from the glass surface to the basin.

**Table 4. Energy Balance on a solar distillation pyramid type.**

| No. | Process                      | In   | Out  |
|-----|------------------------------|------|------|
| 1.  | $Q_{solar}$                  | 462.39 | 270.08 |
|     | a) $Q_{abs, c}$              | 51.59  | - |
|     | b) $Q_{refl, c}$             | 29.99  | - |
|     | c) $Q_{trans, c-b}$          | 87.90  | - |
| 2.  | $Q_{abs, basin}$             | -     | 35.40 |
| 3.  | $Q_{refl, w&b}$              | -     | 57.23 |
| 4.  | $Q_{stored, w}$              | -     | 27.68 |
| 5.  | $Q_{conv, b-g}$              | -     | 14.46 |
| 6.  | $Q_{rad, b-g}$               | -     | 43.59 |
| 7.  | $Q_{evap}$                   | -     | 71.36 |
| 8.  | $Q_{conv, g-a}$              | -     | 58.99 |
| 9.  | $Q_{rad, g-a}$               | -     | 25.76 |
| 10. | $Q_{lost}$                   | -     | 27.32 |
|     | Total                        | 631.87 | 631.87 |

The efficiency of solar distillation pyramid type is about 52.93%. Design problems encountered with solar stills are brine depth, vapor tightness of the enclosure, distillate leakage, methods of thermal insulation, and cover slope, shape, and material [22].

4. Conclusions

The solar distillation pyramid type produced 2317 mL of fresh water for 3 days of observation. Freshwater quality from the desalination process fulfills SNI 01-3553-20215 of drinking water, with a salinity of 0%, pH of 6.5, EC of 8 $\mu$S/cm, and TDS of 9 mg/L. The efficiency of solar distillation pyramid type is about 52.93%. This technology is a widely feasible solution for coastal communities because it is very easy to construct and achieves higher reliability and cost minimization.

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