Jurnal Polimesin
Department of Mechanical Engineering
State Polytechnic of Lhokseumawe
http://e-jurnal.pnl.ac.id/polimesin

e-ISSN : 2549-1999 No. : 3 Month : June
p-ISSN : 1693-5462 Volume : 22 Year : 2024

Article Processing Dates: Received on 2024-01-08, Reviewed on 2024-05-17, Revised on 2024-06-04, Accepted on 2024-06-08 and Available online on 2024-06-29

Effect of tubular-typed charcoal height variations on efficiency in passive interfacial solar desalination

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Abstract

Passive solar desalination is a process of reducing the salt content of salt water to produce fresh water by utilizing solar heat. In recent years, interfacial heating has been proposed as an alternative to evaporation by creating localized heat on the water surface. Charcoal is an absorbent, heat storage, and wettability material, so the evaporation process not only occurs on the surface of seawater but also on the surface of the charcoal, which results from this wettability. The height of the charcoal indicates the distance the steam travels to reach the glass surface for the condensation process, thereby speeding up evaporation. The experiment was carried out in 4 single-slope-type basins using tubes filled with charcoal as high as 30, 40, and 50 mm for 8 hours in the sun. The results showed that adding heat-absorbing material to the basin was able to accelerate seawater to reach its boiling point so that it could evaporate. The temperature and humidity in each basin also have a similar changing trend where temperature is strongly influenced by solar radiation. The use of charcoal can also increase the rate of convection and evaporation heat transfer in the basin, as well as the maximum efficiency in basin 4 with an efficiency value of 56.40%, basin 2 at 53.17%, basin 3 at 51.62%, and basin 1 44.17%. Efficiency is obtained from the desalination efficiency equation, namely the ratio of the latent heat of vaporization to the solar energy entering the system.

Keywords:

Solar desalination, distillation, solar still, interfacial evaporation, charcoal.

1 Introduction

Clean water is a primary human need. Lack of clean water supply for consumption is a big problem. The scarcity of clean water coincides with the massive growth of the world population, agriculture, and industrialization. According to the United Nations, only 0.5% of the 1.4 billion km^3 of water on earth is available and accessible to support all life. One-third of the world's population suffers from a shortage of freshwater resources [1]. To overcome this problem, various technologies have been developed to produce fresh water suitable for consumption from salt water. This process is known as desalination.

Desalination in general is the process of removing salt from seawater or brines. Many desalination methods have been developed, such as membrane desalination, reverse osmosis, electrodialysis, multistage flash distillation, multi-effect distillation [2], and solar-driven interfacial desalination [3]. Among these methods, solar-driven interfacial desalination has attracted attention due to its high efficiency, low cost, and portability compared to other methods [4].

The results showed that the productivity of fresh water from solar desalination would increase if thermal storage material were added to the process of solar stills. This material is a new solution because it helps increase heat and mass transfer in solar stills [5].

Apart from containing carbon, wood charcoal has many pores, and a high energy absorption capacity, and produces a larger radiant and convective heat transfer surface [6], so that the use of block charcoal can increase improvements by 8% [7]. Charcoal briquettes derived from wood have hight heat energy absorption and high porosity, thereby increasing efficiency [8], as do coconut shell charcoal briquettes [9].

Comparative studies of distillate yields at different water depths, with three different Phase Change Materials (PCMs) stored in six copper cylinders made of 1 mm thick sheets, have also been investigated [10]. The results of the research show that the copper cylinder filled with phase change material increases the productivity of solar stills.

Research on using nanocarbons with a size of 50 nm-sized produced from camphor burning has been carried out in 2020 [11]. The results showed that the new *Cinnamomum camphora* incorporated in a polyvinyl alcohol (C@CPVA) evaporation system produces steam at a rate of 1.53 kg m^2 h^{-1} under sunlight with an outstanding photothermal efficiency of 92.38% due to its indirect capillary path design.

Examined a single-slope type solar still by adding charcoal to the bottom of the basin. Experiments were carried out using 3 liters of seawater with variations in the mass ratio of charcoal to water, namely 1:50, 1:100, and 1:500. The results showed that the water temperature reached 49°C at a variation of the mass ratio of charcoal to water of 1:50. The addition of charcoal increases the seawater temperature significantly, thereby increasing the rate of evaporation. In addition, charcoal is also able to filter impurities up to more than 60% Chemical Oxygen Demand (COD) [12].

Based on the problems above, a study was conducted to evaluate the potential of charcoal as a salt adsorbent amd hydrophilic material, its thermal conductivity in absorbing solar energy in solar distillation, and its potential to help the capillary properties of water. The use of charcoal is expected to increase the rate of evaporation in seawater. This evaporation mechanism is assisted by a tube filled with charcoal placed in water.

2 Materials and Methods

2.1 Solar Still Specification

The solar still used in this study is a single-sloping basin type with a slope of 30°. The basin was made of 12 mm thick plywood with dimensions of 33×33 cm. The inside of the basin was covered with a 2 mm thick black acrylic sheet containing 2 liters of seawater. The height of the front wall is 10 cm, and the height of the back wall is 27 cm. The plastic material is also used as a distillation channel so that the condensed vapor flows down the glass and then out of the basin. Cover made of 3 mm transparent glass, dimensions 36×33 cm (Fig. 1).

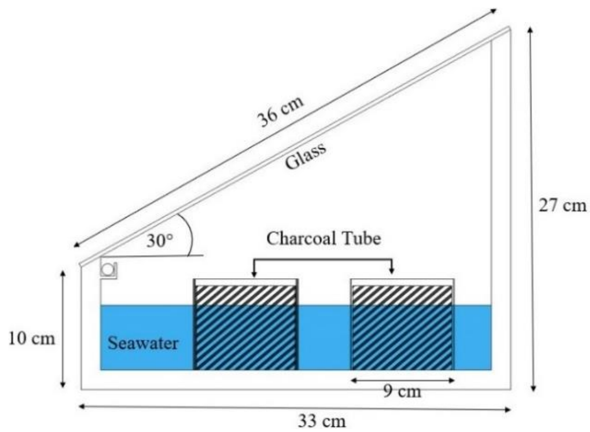


Fig. 1. Dimension of solar still.

2.2 Charcoal Preparation

Kusambi wood (*Schleicera oleosa*) was chosen because it is abundant in East Nusa Tenggara and is often used by the community as a natural fuel for daily and industrial needs because it has good resistance to charcoal. Charcoal made from dry stems of kusambi wood (*Schleichera oleosa*) goes through a burning process for 8 hours [8], then is ground with a grinding machine and sieved with a shaker sieve until charcoal powder measuring 60 mesh is obtained [5]. Then the charcoal is put into a tube whose bottom is covered with flannel cloth (Fig. 2). Each tube measures 75 grams for a 30 mm tube, 100 grams for a 40 mm tube, and 125 grams for a 50 mm tube. The tubes containing charcoal are placed in a basin of six tubes each. Specification value of the charcoal used: (1) charcoal raw material: dry kusambi wood, (2) dry wood density: 0.7845 g/cm^3, (3) combustion temperature: 450ºC, (4) charcoal density: 0.433 g/cm^3, (5) shape: granular (60 mesh).

Fig. 2. Charcoal processing: charcoal after being mashed is put in a tube.

2.3 Experiment and Instrumentation

Data collection was carried out for 8 hours, from 08.00 to 16.00. Temperature data is collected using a Thermocouple Max6675 sensor connected to Arduino Mega as a data logger. Data is collected every minute—placement of sensor points on glass, basin space, charcoal, and seawater [13]. The measuring instrument used to measure solar intensity is the Solar Power Meter SM206, with the specifications: (1) resolution: 0.1 W/m^2, 0.1 BTU/(ft2-h), (2) error range: ± 10 W/m^2 ^{o}C; ± 3 BTU/(ft2-h) or 5% of the measured value, (3) temperature error: ± 10 W/m^2 ^{o}C; ± 3 BTU/(ft2-h) or 5% of the measured value, (4) display: 3–3 /4 LCD screen, maximum displayed numeric value: 3999, (5) range: 0.1–399.9 W/m^2, 1–3999 W/m^2, 0.1–399.9 BTU/(ft2-h), 1–3999 BTU/(ft2-h), (6) sampling time: 0.5 seconds, (7) operation at temperature and humidity: 0^{o}C to 50^{o}C; < 80% RH, (8) storage temperature and humidity: 0^{o}C to 60^{o}C; < 70% RH (Fig. 3).

Temperature and humidity data are measured in reel time every second, but in analysis per 30 minutes, however, this already represents the fluctuating intensity of the sun. Data collection was carried out three times, but because the evaporation rate, efficiency, and desalination water production were the same with each change in solar intensity and environmental temperature, only one data point was analyzed. Data collection was carried out three times, but because the evaporation rate, efficiency, and desalination water production were the same with each change in solar intensity and environmental temperature, only one data point was analyzed.

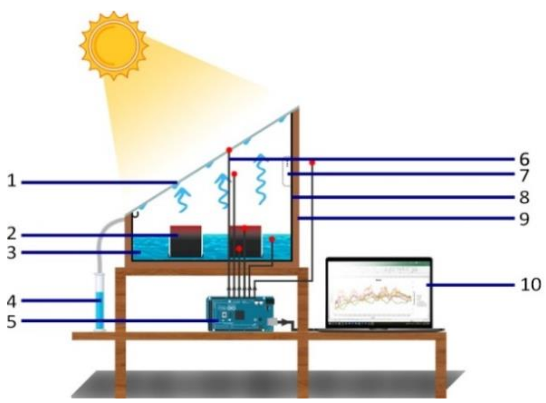


Fig. 3. Experimental set-up of solar still and measuring instruments position.

1. Glass
2. Charcoal tube
3. Seawater
4. Measuring cup
5. Arduino Mega
6. Thermocouple Max6675
7. Elitech thermometer data logger
8. Acrylic sheet
9. Plywood
10. Laptop

3 Results and Discussion

The data analysis used in this study is a mathematical analysis obtained from the calculation formula based on the theory of thermal solar desalination by investigating the effect of variations in charcoal height on changes in temperature, heat transfer, and desalination efficiency.

3.1 Effect of Sun Intensity on Temperature Changes

Sun intensity greatly affects the temperature of charcoal; the increase in temperature is directly proportional to the increase in sun intensity. The temperature data graph as shown in Fig. 4.

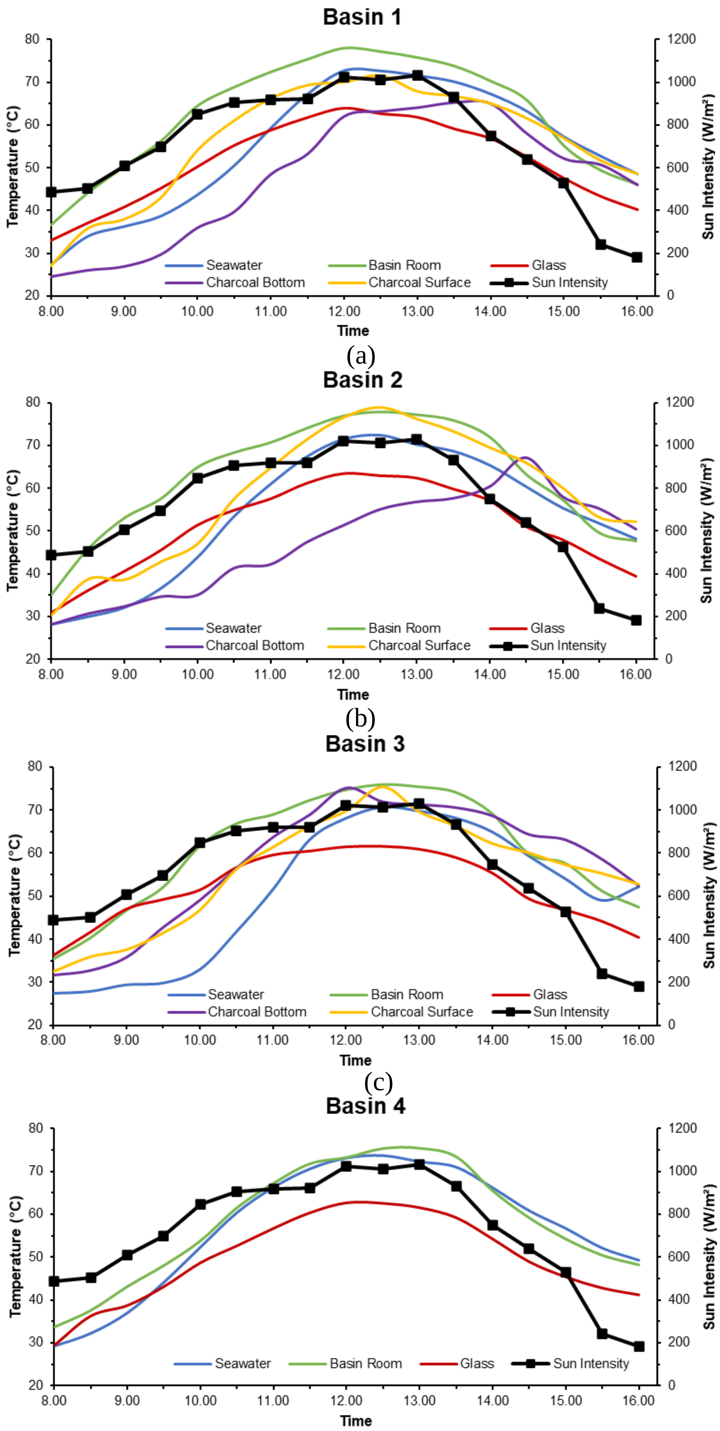


Fig. 4. Graph of sun intensity and temperature correlation on each basin with charcoal height variations (a) 30 mm height; (b) 40 mm height; (c) 50 mm height; (d) basin with no charcoal.

In basin 1, with a charcoal height in the tube of 30 mm, the tube floats or fills part of the volume of water but does not touch the bottom of the basin. This is because the mass of charcoal per tube is 75 grams. As the temperature of the charcoal rises, more energy is added to the seawater. This energy is stored in the form of kinetic energy in seawater molecules. Seawater molecules tend to move quickly until the water expands and reduces its density. Decreasing the density of a fluid generally makes it lighter and tends to make the fluid move upward. Therefore, seawater can continue to rise through the pores of the charcoal to the surface of the charcoal. Basin 2 uses a tube with a charcoal height of 40 mm, and the mass of charcoal each tube is 100 grams. The graphic pattern shown in Fig. 4 is similar to the graph in basin 1, but the surface temperature of the charcoal in basin 2 is higher than the surface temperature of the charcoal in basin 1. This is due to the addition of charcoal material, which was previously in basin 1 only with a thickness of 30 mm and a mass of 75 grams per tube. Meanwhile, basin 2 has a thickness of 40 mm and a mass of 100 grams. This higher temperature of the charcoal occurs because the distance between the surface of the charcoal and the water level is relatively far so that the sun's heat received can be maximized properly by the charcoal tube. This will accelerate the capillarity of seawater so that the evaporation process in basin 2 will occur a little faster compared to basin 1.

The addition of the mass of charcoal in basin 3 to 125 grams and the thickness, which also increased by 10 mm to 50 mm, produces a graphic pattern that is slightly different from basins 1 and 2. The pattern appears to tend to fluctuate because more solar heat is needed, which is sufficient to heat the tube and the charcoal itself before evaporating the seawater. The temperature of the charcoal can be higher if the intensity of sunlight is also high, such as at 12.00–13.00. However, if the intensity of the sun is low, the charcoal tube tends to store water because, at that time, the charcoal requires more solar energy to help process the capillary action of seawater through the 50 mm thickness of the charcoal. This does not stop the evaporation process; evaporation is still ongoing, but at a slower rate compared to evaporation in basin 2. Basin 4 is the basin with the widest cross-sectional area for receiving solar energy among the other three basins because it does not use charcoal tubes covering the water surface. The test results show that water is no better at storing heat energy than charcoal. This is indicated by the glass surface of basin 4, which fogs more slowly than basins 1, 2, and 3 (Fig. 5).

Fig. 5. The fogging process on the glass surfaces of basins 1, 2, 3 and 4 at 9:30.

The convection heat transfer coefficient h_{cwg} between the water surface and the solar desalination glass is calculated using the Eq. 1 [14], [8], and [9]:

$$h_{cwg} = 0.884\left[(T_w - T_{gi}) + \frac{(P_w - P_{gi})}{(2016 - P_w)}\right]^{1/3} \quad (1)$$

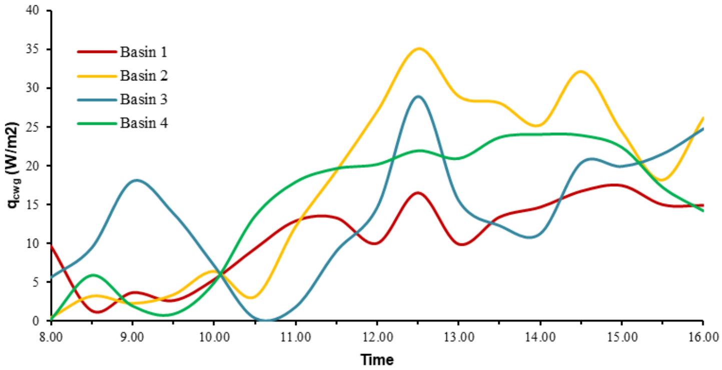
While the convective heat transfer rate is given by the heat transfer coefficient and the temperature difference between the two surfaces as Eq. 2 [15], [16], and [17],

$$q_{cwg} = h_{cwg}\,(T_w - T_{gi}) \quad (2)$$

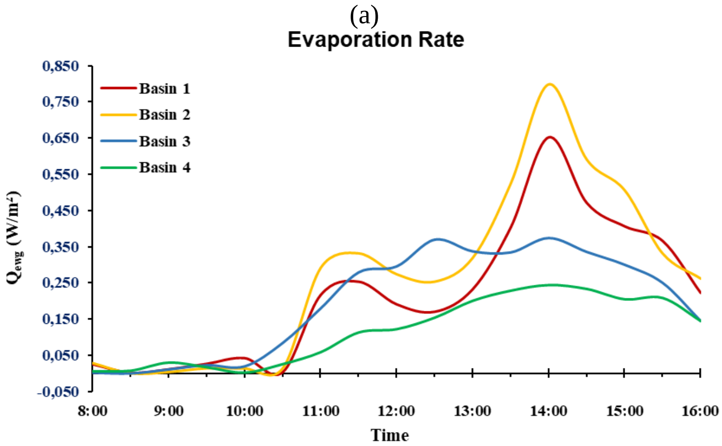
The evaporation rate is the parameter that controls the distillation output. The evaporation heat transfer coefficient from the water surface of the basin to the inner surface of the cover glass can be expressed by the Eq. 3 [15], [14], [8], and [9]:

$$h_{ewg} = \frac{9{,}15 \times 10^{-7} h_{cwg}(P_w - P_{gi})\, h_{ev}}{(T_w - T_{gi})} \quad (3)$$

The two graphs in Fig. 6 show the highest convection heat transfer calorific value and evaporation rate coefficient in basin 2 until 12.30, followed by basin 3, basin 4, and basin 1. Then it decreased due to a decrease in solar intensity. This data shows that basin 2 has better convection and evaporation rates than the other three basins.



(a)



(b)

Fig. 6. Heat transfer rate inside solar still. (a) Convection heat transfer rate; (b) evaporative heat transfer coefficient.

3.2 Distillate Productivity

Distillate is the end product of the distillation process which is created from the capillary process, the process of evaporation and condensation of seawater. In this study, distillate productivity is strongly influenced by the received heat energy source, namely solar radiation. Because the more sunlight, the higher the temperature, and seawater can reach its boiling point. However, as temperature increases, relative humidity decreases, making it more difficult for water vapor molecules to reach the dew point. This reduces the rate of condensation and distillate formation. Fig. 5 shows that in basins 1, 2, and 3 they have started producing distillate at 9.00. While basin 4 just produced distillate at 09.30. This data proves that the use of charcoal tubes as heat storage has succeeded in increasing the evaporation rate of seawater and distillate productivity, but the intensity of the sun also affects distillate productivity. It can be seen at 14.00 when the intensity of the sun begins to decrease, which is generally caused by clouds covering the sun. Basin 3 with a thickness of 50 mm shows less distillate productivity than other basins due to the slower capillarity process. Whereas in basin 4, without the use of charcoal, distillate productivity continues to increase because heat from the intensity of sunlight is directly received by the water surface, which causes the evaporation process to continue so that a lot of water vapor sticks to the glass. When the intensity of the sun decreases, there is a decrease in room temperature and as a result, condensation occurs. In addition, it fogs up the water vapor on the glass surface and does not block the intensity of the sun from entering to heat the water in the basin, which results in a better condensation process and better freshwater productivity, even though the surface temperature of seawater is not as high as when using this material, charcoal. The total distillate between basins 1, 2, 3, and basin 4 is presented in Fig. 7. Maximum distillate results were obtained in basin 4 of 184 ml, followed by basin 2 of 174 ml, basin 3 of 169 ml, and basin 1 of 144 ml.

Charcoal has an effect on the productivity of desalinated water because charcoal not only plays a role in absorbing and storing heat from the sun to speed up the evaporation process of seawater but also in order for capillarity and wedability events to occur. Meanwhile, the height of the charcoal shows the distance between the evaporated steam and the inner surface of the glass for the condensation process to occur.

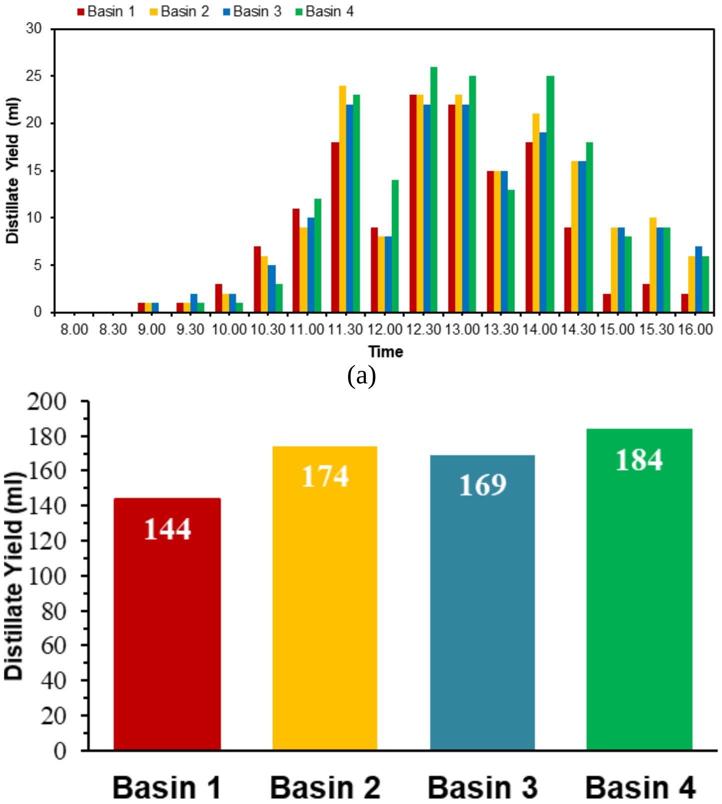


Fig. 7. Distillate productivity graph. (a) Distillate yield every 30 minutes; (b) total production of distillate for 8 hours.

3.3 Solar Desalination Efficiency

Efficiency is defined as the ratio of the total latent heat generated by the evaporation of the distillate to the incoming heat of the solar energy system [18]. This can be expressed mathematically as Eq. 4,

$$\eta_d = \frac{m_d \times h_{fg}}{A \times I_s} \times 100\ \% \qquad (4)$$

where m_d is the distillate production, h_{fg} is the latent heat of evaporation, A is the receiver area of the solar desalination system, and I_s is solar radiation.

The latent heat of evaporation is the amount of heat needed to change the seawater phase into steam. From Fig. 8(a), it can be seen that basin 2 has the lowest latent heating value compared to the other three basins. This shows that basin 2 requires less heat energy to evaporate seawater. In contrast to basins 1, 3, and 4, basin 2 with a charcoal height of 40 mm is able to increase the absorption of heat in seawater because, with this height, the charcoal does not only float on the surface of the water but rather fills part of the volume of water so that the seawater can reach the boiling point more quickly.

A comparison of desalination efficiency between basins 1, 2, 3, and basin 4 is shown in Fig. 8(b). It can be seen at 14.30 that the desalination efficiency in basin 2 is the highest, with a value of 94.36%, followed by an efficiency value of basin 3 of 89.81%, basin 1 at 69.17%, and basin 4 at 49.00%. This proves that the efficiency value of the basin with tubes filled with charcoal has a high value because it is supported by adequate sunlight intensity. Meanwhile, at 16.00, the efficiency of each basin decreased with the value of each basin, namely basin 3 with an efficiency value of 49.80%, basin 2 at 49.65%, basin 4 at 20.76%, and basin 1 at 15.57%. Desalination efficiency is influenced by four factors: distillate productivity per hour, latent heat of evaporation, sun intensity, and the area of absorbing sunlight. Therefore, even though basin 4 produces more total distillate than the other basins, with a water cross-section of 900 cm^2, the efficiency value is smaller when compared to the surface area of the charcoal tube, which is only 381.51 cm^2.

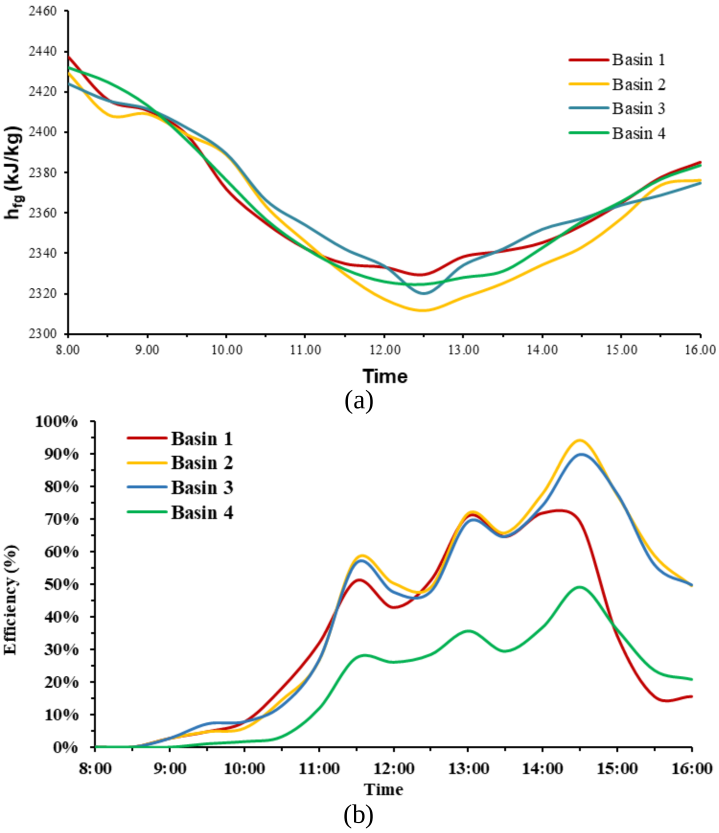


Fig. 8. Thermal analysis for each basin. (a) Latent heat (enthalpy) of evaporation; (b) desalination efficiency.

4 Conclusion

The desalination process using the passive solar distillation method in this study shows that the height of the charcoal affects the evaporation rate, desalination efficiency, and desalination water production. The height of the charcoal indicates the distance between the evaporation process on the charcoal-absorbing surface and the condensation process on the cover glass. The higher the charcoal the greater the evaporation rate, desalination efficiency, and desalinated water production. However, if it is too high, it will reduce efficiency and production because the high temperature on the surface of the charcoal, will affect the condensation temperature on the cover glass. Charcoal not only plays a role in absorbing and storing heat from the sun to speed up the process of evaporation of seawater but also to ensure capillarity and wet ability events occur. Adding heat-absorbing materials to the basin can speed up seawater reaching its boiling point so it can evaporate. By increasing the evaporation rate, the productivity of the distillate will also increase. Thus, maximum efficiency is found in basin 3 with a charcoal height variation of 50 mm with an efficiency value of 49.80%, basin 2 with a charcoal height variation of 40 mm with an efficiency value of 49.65%, and basin 4 without charcoal with an efficiency value amounted to 20.76% and the variation in charcoal height in basin 1 was 30 mm with an efficiency value of 15.57%. Desalination efficiency is influenced by four factors, namely: hourly distillate productivity, latent heat of vaporization, solar intensity, and sunlight absorption area.

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