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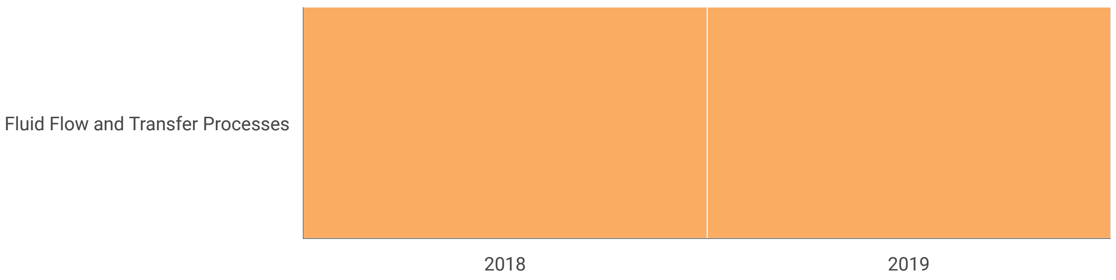
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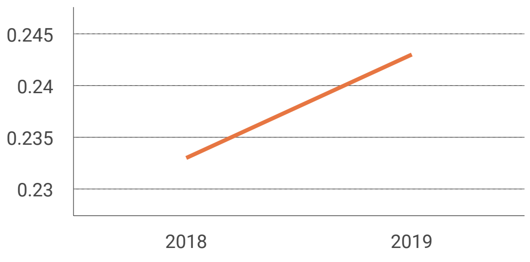
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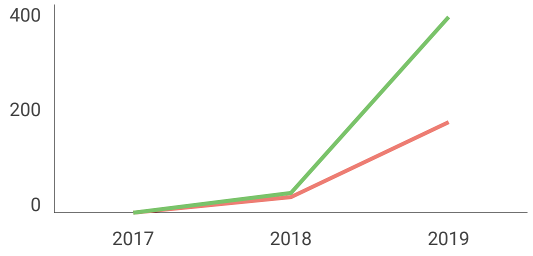
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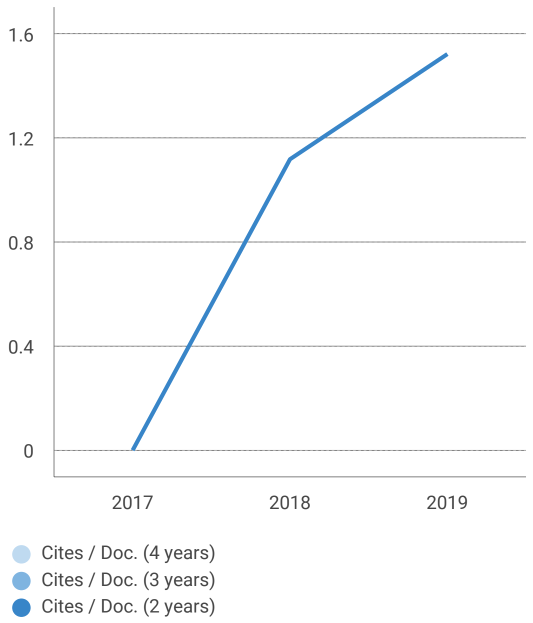
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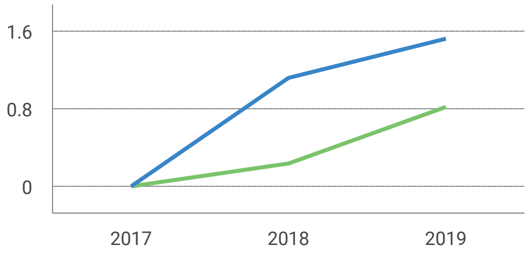
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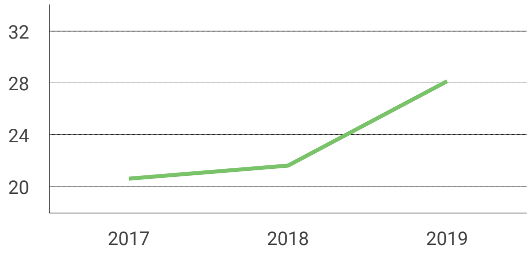
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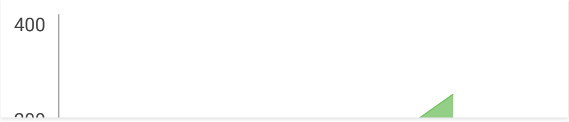

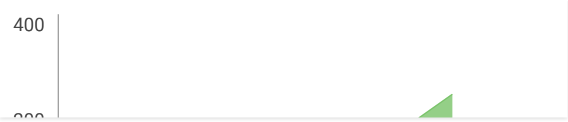

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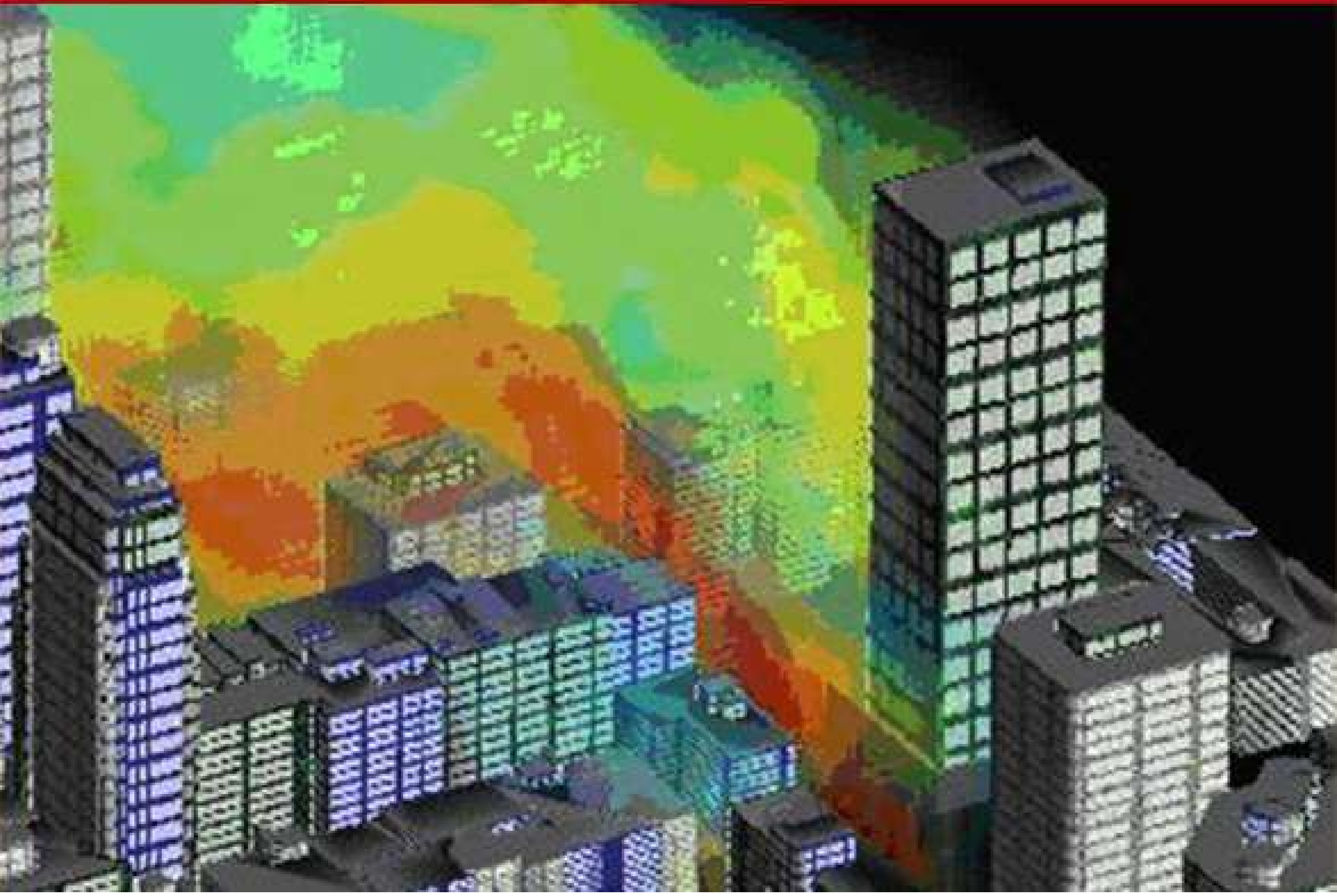

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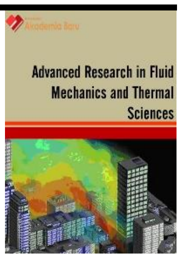

Iron Sand as a Heat Absorber to Enhance Performance of a Single-Basin Solar Still

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ABSTRACT

Many researchers already use sensible materials to enhance the performance of solar stills, but only a few use iron sand as a heat absorber in single-basin solar stills to enhance the performance, as demonstrated in this experiment. The study was conducted in the period August–September 2018 and used four solar stills with dimensions of 420 mm × 305 mm and a cover with a slope of 30 degrees. Three of the solar stills contained iron sand 20 mm high. The height of water in the three solar stills was 15 mm (V1), 20 mm (V2) and 25 mm (V3), so that the surface of the water would be: below the surface of the iron sand, on the same level as the surface of the iron sand, and above the surface of the iron sand, respectively. The fourth solar still, filled with only 20 mm (P) of water, was a benchmark for the others. From the results, we inferred that the heat absorbed by the iron sand enhanced the total heat transfer coefficients inside the solar still. This result agreed with exergy and overall efficiency of solar stills. The results showed that the fresh water produced by increasing V1, V2 and V3 against P was 1.5%, 51.8% and 57.1%, respectively. Therefore, we conclude that iron sand significantly enhances the productivity of a solar still. The best result was obtained when the water surface was higher than the iron sand surface.

Keywords:
Desalination; solar still; iron sand, porous media

1. Introduction

Fresh water accounts for only 2.5% of the water on Earth, and the rest is seawater [1]. Unfortunately, fresh water is decreasing with an increase in consumption and climate changes [2]. Because there is a huge quantity of seawater, it is considered a potential source of fresh water, particularly in countries that have a long coastline or are island countries [3], although seawater must first be processed to obtain fresh water.

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A solar still is one of the most widely used methods [4] of processing seawater into fresh water in rural locations, with a low population because it is cheap, easy to handle and suitable for producing up to 200 m^3/day of fresh water [5]. A solar still is a simple device based on the greenhouse effect [6], with only one chamber to evaporate and condense basin water. Although it is simple in design, the solar still continues to be studied for performance improvements.

Many methods and materials have been used for solar still productivity improvements, and a number of efforts have been made to increase productivity by using heat storage from sensible heating materials. For instance, one experimental study of carbon powder used charcoal particles as an absorber medium and increased the productivity of a solar still by up to 15% [7]. El-Sebaii used sand as a sensible storage material under the basin liner [8], and in another study, sand was used instead of servotherm medium oil as a sensible heat storage material, placed beneath the basin liner [9]. In another study, there was as much as a 35% improvement in a solar still that used carbon powder as a porous solar absorber [10]. Other materials that have been used as sensible heat storage materials include the quartzite rock, red brick pieces, cement concrete pieces, washed stones and iron scraps that were placed in a solar still in one study [11]. Similarly, black jute clothes acted as porous absorbers in the basin water inside a solar still in other research [12]. Extended porous fins made up of old blackened cotton rags were partially dipped inside the basin of the still in yet another study [13]. And in another, blackened Portland cement used as heat storage resulted in a 39% increase in the production of fresh water [14]. A modified solar still using silica sand and layered with black coal powder at its surface was used to study heat and mass transfer [15] in comparison to a conventional solar still. Omara and Kabeel compared the performance of two solar stills, one containing yellow sand and the other one containing black sand. The results showed that the performance of the solar still with black sand was better than both the conventional still and the one with the yellow sand [16]. A solar still using fine black stones measuring 1 cm, 1.5 cm and 2 cm in diameter as a porous absorber was compared with a conventional still, which does not have that property [17]. Although many studies have already been conducted using sensible materials to enhance the performance of a solar still, only a few of them used sand, and to the best of the authors' knowledge, no other research has used iron sand as a heat absorber. In addition to its low cost and ready availability, iron sand has a higher heat storage capacity than sand, rock, concrete or brick [18,19]. This encourages the use of iron sand as an absorber.

This study investigated the outdoor performance of a single-basin solar still using iron sand as a heat absorber to enhance the still's performance because iron sand used as an absorber can increase the surface area of a solar still. Furthermore, to find the effect of porosity in iron sand, the water surface level was set lower than the iron sand surface, at the same level as the iron sand surface and higher than the iron sand surface. This use of varied water surface levels with porous media has not been previously studied in solar stills. This article also assesses the heat and mass transfer enhancement from using a porous absorber, and an evaluation of its efficiency.

2. Methodology

2.1 Internal Heat Transfer in Evaporation Process

The evaporation process in a solar still begins with the plate's absorption of heat energy from the sun followed by its transfer to the basin of water, and then the heat in the basin water is transferred to the solar still cover. The heat transfer that occurs from the basin water to the still cover glass is the sum of the convection, radiation and evaporation of heat transfers [20].

$$q_t = h_t(T_w - T_v) \tag{1}$$

$$h_t = h_c + h_r + h_e \tag{2}$$

According to Dunkle’s model, the convective heat transfer coefficient (h_c) can be expressed as follows [21]

$$h_c = 0.884 \times \Delta T^{\frac{1}{3}} \tag{3}$$

Because the condition of the values C = 0.884 and n = 1/3 of Dunkle’s model is related to some accurate conditions [22], these values will change when the conditions change. The convective heat transfer can also be obtained from the relationship of the Nusselt number with the heat transfer coefficient.

$$Nu = \frac{h_c \cdot L}{k_f} = C(Gr \cdot Pr)^n \tag{4}$$

$$h_c = \frac{k_f}{L} C(Gr \cdot Pr)^n \tag{5}$$

$$Gr = \frac{\beta g L^3 \rho^2 \Delta T}{\mu} \tag{6}$$

$$Pr = \frac{\mu \cdot C_p}{k_f} \tag{7}$$

$$\Delta T = (T_w - T_v) + \frac{(P_w - P_v) T_w}{268.9x10^3 - P_w} \tag{8}$$

The radiative heat transfer coefficient ($h_{r,w\text{-}v}$) and the evaporative heat transfer coefficient ($h_{e,w\text{-}}$) are calculated using the following equations

$$P_w = \exp\left[25.317 - \left(\frac{5144}{T_w + 273}\right)\right] \tag{9}$$

$$P_v = \exp\left[25.317 - \left(\frac{5144}{T_v + 273}\right)\right] \tag{10}$$

$$h_r = \varepsilon_{eff} \times \sigma \times [(T_w + 273)^2 + (T_v + 273)^2] \times (T_w + T_v + 546) \tag{11}$$

The effective emittance is given as follows

$$\varepsilon_{eff} = \left(\frac{1}{\varepsilon_w} + \frac{1}{\varepsilon_{gi}} - 1\right)^{-1} \tag{12}$$

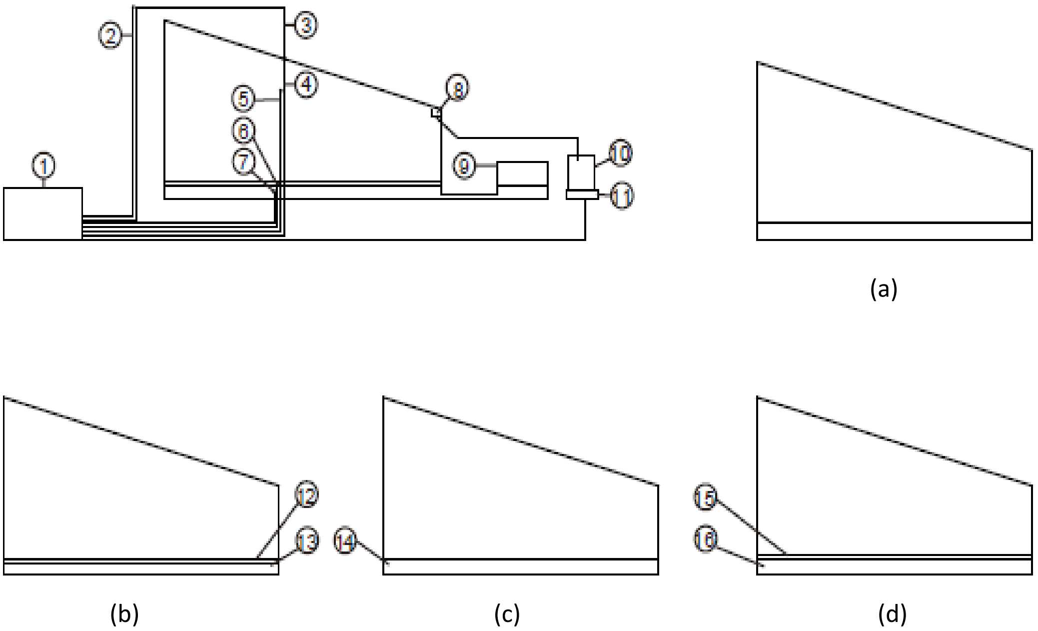
$$h_e = 16.273 \times 10^{-3} \times h_c \times \left[\frac{P_w - P_v}{T_w - T_v}\right] \tag{13}$$

The efficiency of a solar still is determined by the yield of the condensate multiplied by the latent heat of evaporation and divided by the daily solar radiation [23].

$$\eta = \frac{\sum m_d \times h_{fg}}{\sum I(t)_s \times A_s \times 3600} \tag{14}$$

2.2 Experimental Setup

Four single-basin solar stills were fabricated with 2 mm stainless steel plates (SUS304) with covers made of 3 mm glass and with practical dimensions of 403 mm × 305 mm. Three of the solar stills were filled with iron sand up to 20 mm, while one solar still contained only water. The iron content in the iron sand varied depending on the area where it was mined. In this experiment, the iron sand containing 70.3% iron was mined from Glagah Beach, Kulonprogo, Yogyakarta in Indonesia. Figure 1 shows the four solar stills used in this study. Figure 1(a) is a solar still that contained only basin water, labelled P. Figure 1(b) is a solar still that contained iron sand at a height of 20 mm and basin water to a height of 15 mm, labelled V1. Figure 1(c) is a solar still that contained iron sand and basin water to a height of 20 mm, labelled V2. Figure 1(d) is a solar still that contained iron sand to a height of 20 mm and basin water to a height of 25 mm, labelled V3. The study was conducted on 19 August 2018, 29 August 2018 (see Figure 2) and 1 September 2018, from 08.00 to 17.00 on each day, without considering the solar radiation conditions. The temperature data were collected using a calibrated type K thermocouple, which has an accuracy of 0.1%, at intervals of 15 min. A digital anemometer 0–30 m/s, with an accuracy of 0.1 m/s, was used to measure the wind speed. The water levels inside the solar stills were maintained at fixed levels by using a buffer tank outside the stills.



(a)

(b) (c) (d)

Fig. 1. Single-slope solar still containing (a) basin water to a height of 20 mm, P; (b) iron sand up to a height of 20 mm and basin water up to a height of 15 mm, V1; (c) iron sand and basin water both up to a height of 20 mm, V2; and (d) iron sand up to a height of 20 mm and basin water to a height of 25 mm, V3. 1 = Data collector; 2 = solar radiation sensor; 3 = T_{go} sensor; 4 = T_{gi} sensor; 5 = T_v sensor; 6 = T_w sensor; 7 = T_s sensor; 8 = gutter; 9 = water basin buffer; 10 = freshwater collector; 11 = weighing; 12 = iron sand in V1; 13 = mix of water and iron sand in V1; 14 = mix of water and iron sand in V2; 15 = basin water in V3; and 16 = mix of water and iron sand in V3.Construction of experimental set up (a) solar still control containing only basin water and (b) solar still containing 20 mm iron sand and 15 mm basin water

Fig. 2. Experiment of P, V1, V2 and V3 on 29 August 2018

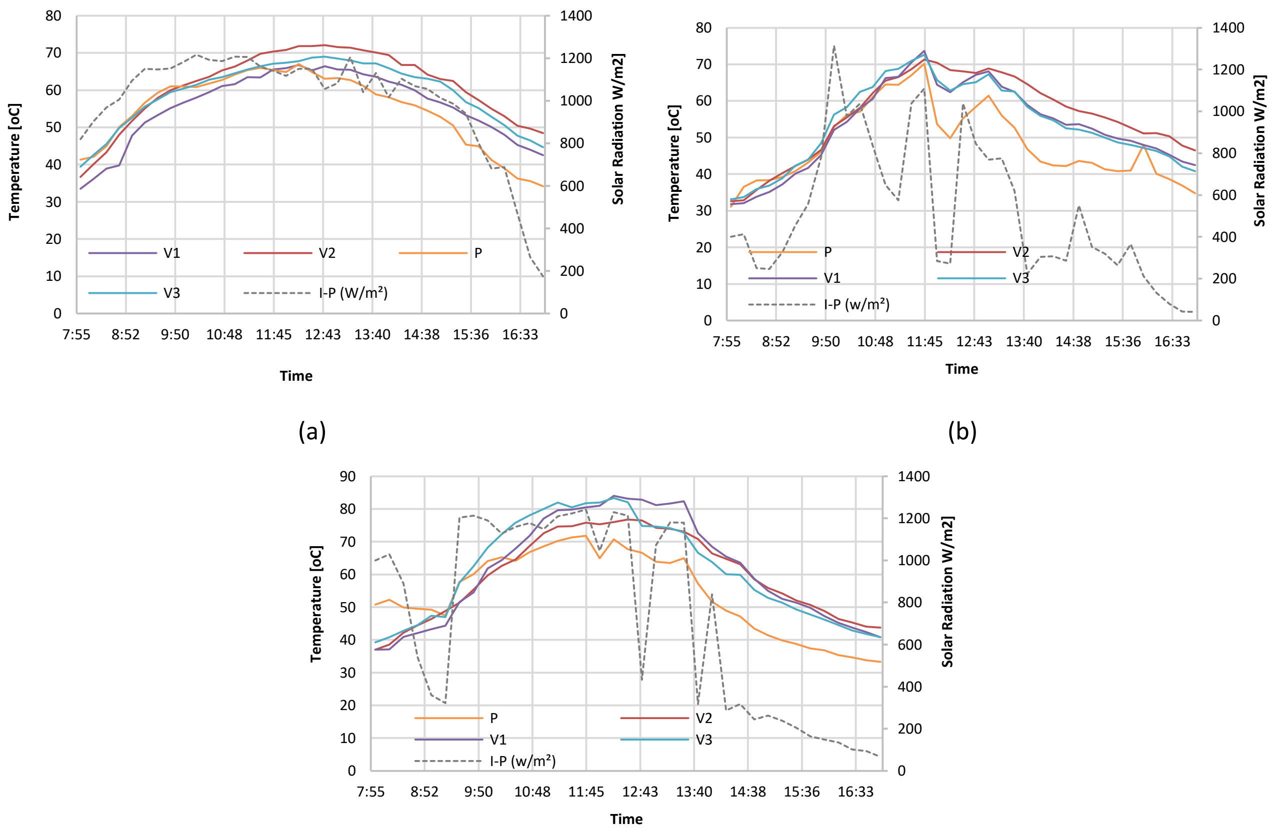
3. Results

3.1 Experimental Data

The experiment results are shown in Figure 3–5, where each figure represents the solar stills on a certain date. As can be seen in Figure 3, the water temperature in the solar stills fluctuated in response to solar radiation, although the response was different for each type of still.

In Figure 3, one can see that the water temperatures in solar still P were higher than those in the other three stills irrespective of the solar radiation conditions. After solar stills V2 and V3 were run for 2 hours and V1 was run for 4 hours, the water temperature in solar stills V1, V2 and V3 increased to higher temperatures than in solar still P. This was attributed to the presence of iron sand in three of the stills, where the heat capacity of the sand was added to the heat capacity of the basin plate [24]. Because the heat capacity in these solar stills (V1, V2 and V3) was higher than in solar still P, the water temperature in solar stills V1, V2 and V3 increased more slowly than in solar still P. The heat from the solar stills was stored in the iron sand and then released gradually to the water [8,14,25], resulting in the water temperature increases in stills V1, V2 and V3. Moreover, the water temperature in solar stills V1, V2 and V3 was not responsive to the changes in solar radiation, which was attributed to the iron sand continuing to transfer heat to the water even when the heat from the sun dropped. the pressure difference between the surface of the water and the inside of the glass was the driving force for evaporation, which was proportional to the difference in temperature, the amount of water vapour condensed was proportional to this difference [26,27]. The increase of water temperature drive water evaporation and eventually condense on inside of glass cover.

The condensation process occurring on the inside of the glass cover was directly affected by the difference in temperature between the water and the glass. The glass temperature was sensitive to wind speed, and only a small fraction of solar radiation was absorbed by the glass cover [28]. On top of that, the vapour temperature in V1, V2 and V3 was higher than that in solar still P, as shown in Figure 4.

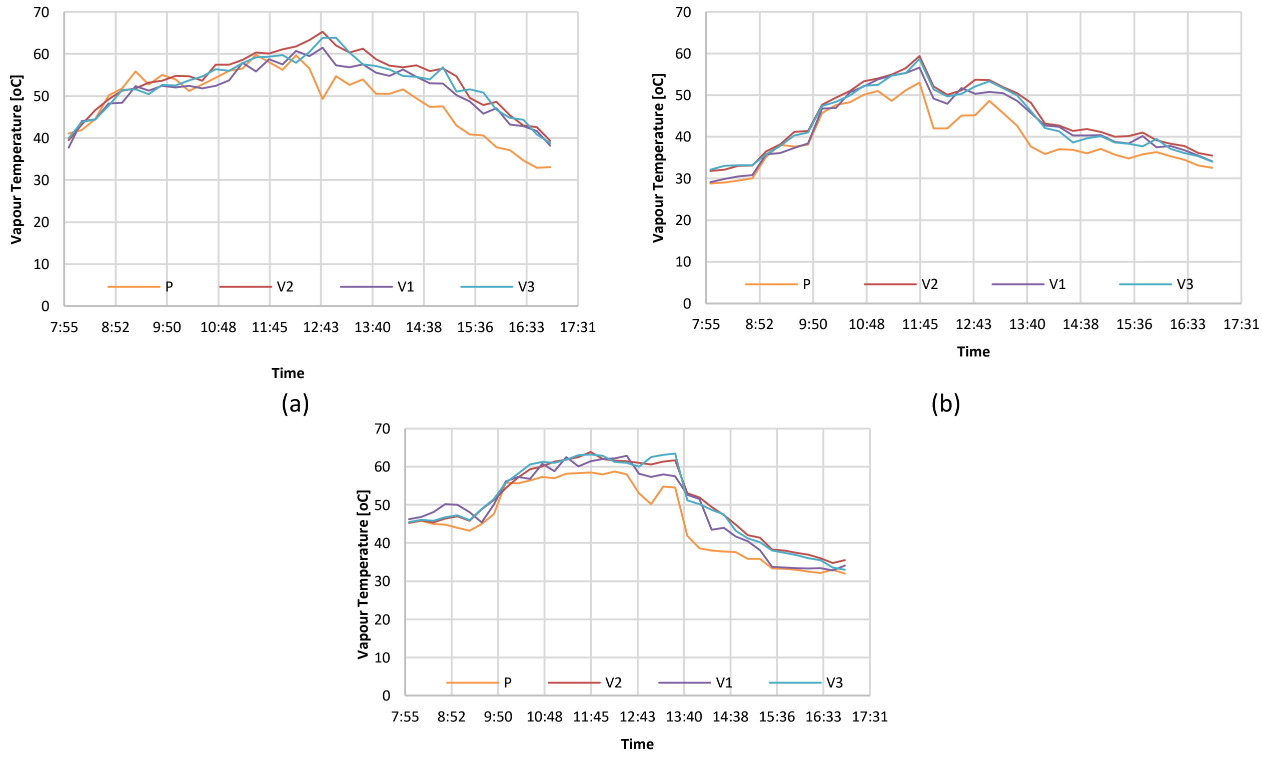


(a)

(b)

(c)

Fig. 3. Water temperature (T_w) of P, V1, V2 and V3 on (a) 19 August 2018, (b) 29 August 2018 and (c) 1 September 20119 August 2018



(a)

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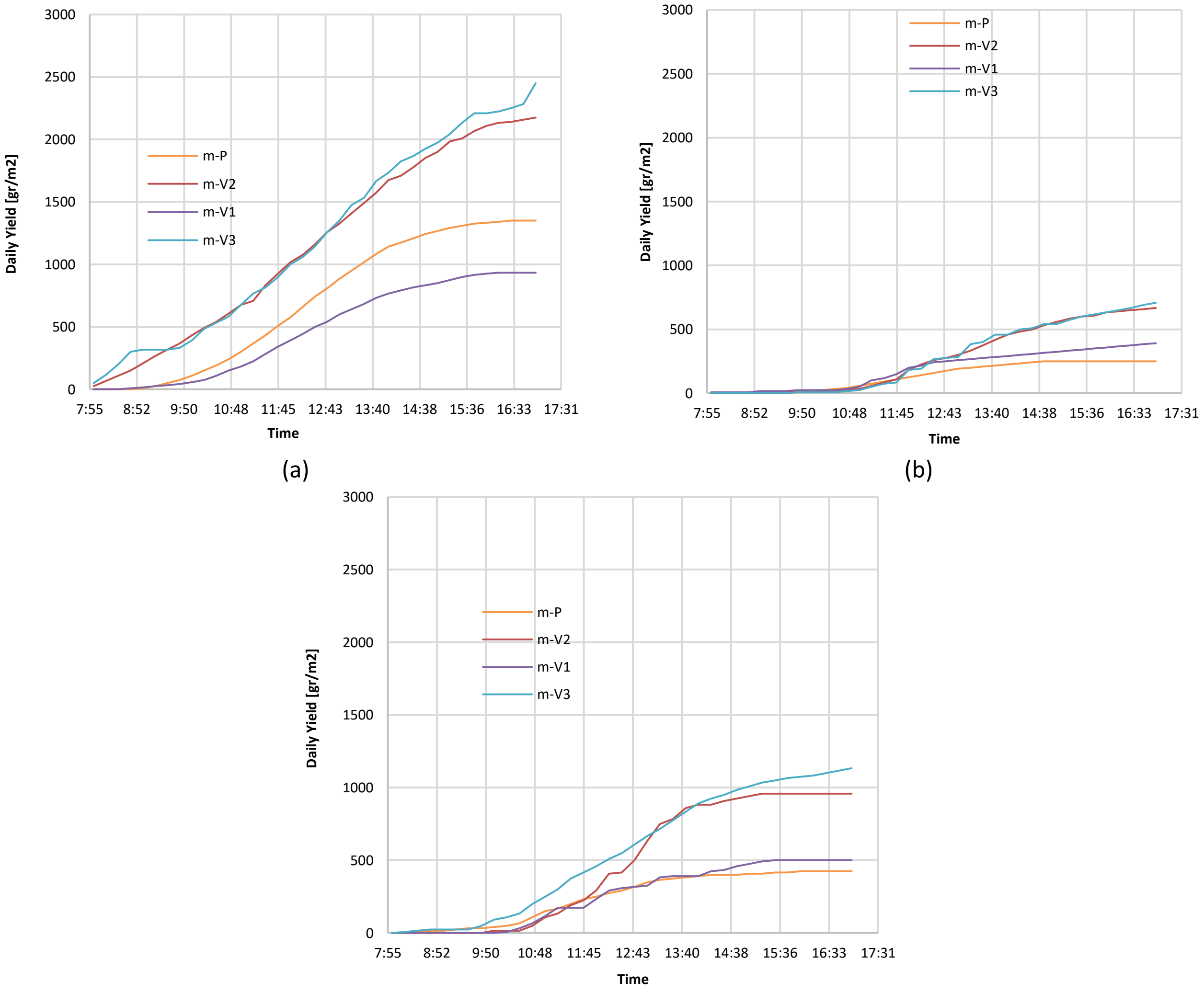
Fig. 4. Vapour temperature (T_v) of P, V1, V2 and V3 on (A) 19 August 2018, (B) 29 August 2018 and (C) 1 September 2018

As shown in Figure 5, the daily yield accumulation of the solar stills containing a sensible heat material (V1, V2 and V3) was higher than in the solar still without a sensible heat material (solar still P), except on 19 August 2018. On this date, the daily yield accumulation of solar still V1 was lower than the yield of solar still P. Although a porous material has a larger surface area for heat transfer to the water [29], The level of water in V1 was lower than the level of the sensible material; therefore, even when the water level rose to the sensible surface of the material by capillarity, the heat that accumulated on the surface of the iron sand heated the inside of the cover glass and increased the temperature of the inner glass [30].



(a)

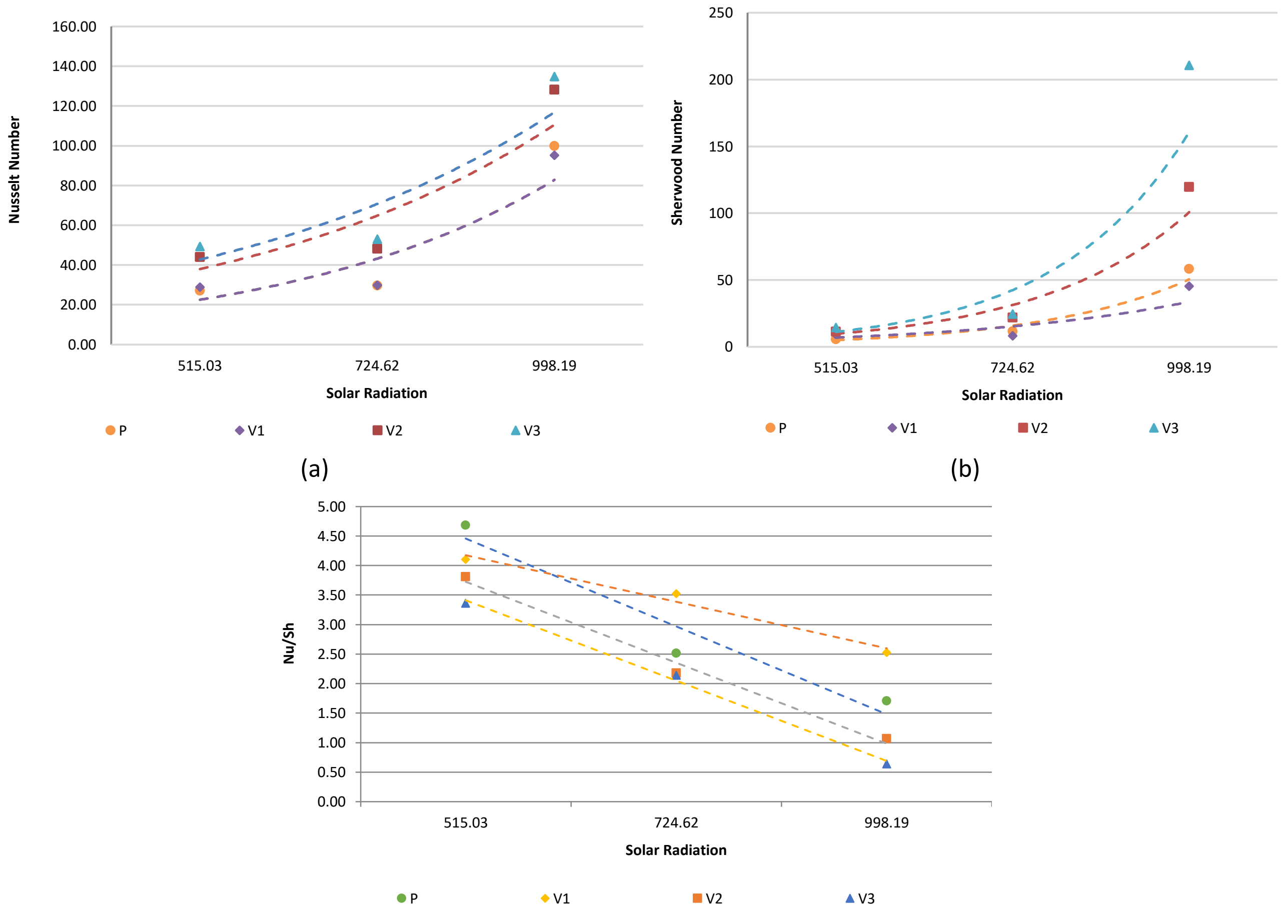
(b)

(c)

Fig. 5. Daily yield of P, V1, V2 and V3 on (a) 19 August 2018, (b) 29 August 2018 and (c) 1 September 2018

3.2 Heat and Mass Transfer

The values of the constant C and n in the Nusselt number were found by using the procedure in the linear regression analysis method [31,32] and the results are used to calculate the Nusselt number. In this study, all of the experiments had a relatively constant Schmidt number of $2.1 < Sc < 2.4$. Because solar radiation is not typical on every experiment date, the average Nusselt number and Sherwood number of the solar stills P, V1, V2 and V3 were grouped by average solar radiation, as shown in Figure 6. Figure 6(a) shows that the Nusselt number of V2 and V3 was higher than those of V1 and P. The greatest heat transfer in the system was that of V3, followed by V2. The heat transfers in solar stills V1 and P were considered the same. In Figure 6(b), the Sherwood number that represents mass transfer is shown. One can see that the mass transfer in solar stills P, V1, V2 and V3 exponentially increased as the solar radiation increased. The greatest result was obtained in V3, followed by V2. The Sherwood number in solar still V1 was higher than in solar still P with solar radiations of 515.03 w/m^2 and 724.62 w/m^2, but at 998.19 w/m^2, solar still P was higher than V1. These results indicate that the convective heat transfer followed by the mass transfer was more active in solar stills V2 and V3 than in the other two stills. With the increase in solar radiation, the temperature and surface pressure of the water increased so that evaporation occurred. The mass that moved upward due to buoyancy also became a medium of heat transfer from water to the inside of the glass cover. Mass and heat transfer processes have an exact analogy [33] if the boundary conditions are the same for a given geometry, so mass transfer results are comparable to heat transfer results. By using the analogy in Figure 6(c), the decrease of heat and mass with increases in solar radiation can be seen. Decreases in the values of the heat and mass analogy are caused by increased heat and mass transfer. The value of mass transfer increases higher than the value of heat transfer so that the analogy value of heat and mass decreases with increasing solar radiation, especially in solar still V2 and V3. From these figures, we inferred that the heat absorbed by the iron sand enhanced the total heat transfer coefficients and mass transfer inside the solar still. Moreover, this result agreed with the overall efficiency in Figure 7.



(a)

(b)

(c)

Fig. 6. Nusselt number (a), Sherwood number (b) and Nusselt/Sherwood (Nu/Sh) analogy factor (c)

Furthermore, in overall efficiency, the most significant increase in efficiency was in solar still V3, as can be seen in Figure 7, and the results obtained in this study indicated that the use of iron sand as a heat absorber in solar stills increased the average efficiency of solar stills V1, V2 and V3, as compared to that of P, by 1.5%, 51.8% and 57.1%, respectively, as shown in Table 1. This result is higher than with using black sand and yellow sand, which increased the average efficiency of solar stills by 42% and 17%, respectively [16].

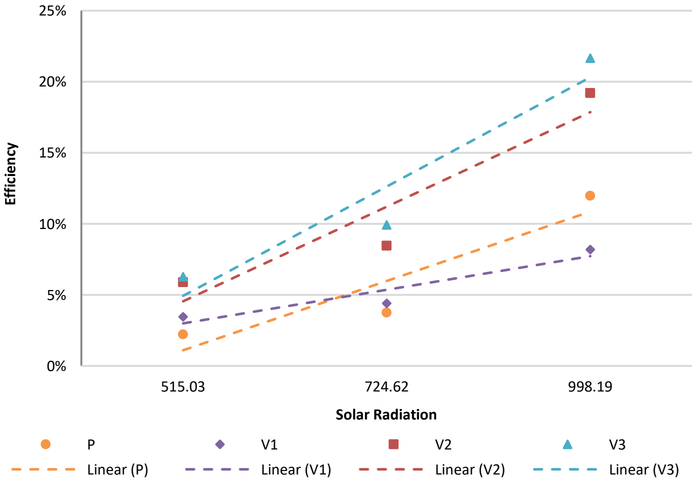


Fig. 7. Solar still overall efficiency

Table 1
Efficiency increase in solar stills V1, V2 and V3 in comparison to solar still P

Date	V1	V2	V3
19 August 2018	−46.0%	37.7%	44.7%
29 August 2018	36.0%	62.3%	64.6%
1 September 2018	14.6%	55;5%	62.1%
	1.5%	51.8%	57.1%

4. Conclusions

The performances of solar stills improved significantly after the implementation of iron sand as an absorber. This improvement was particularly true for solar stills V2 and V3, where the water surface level was the same level as the iron sand surface and 5 mm higher than the sand surface, respectively. Heat and mass transfer for the solar stills with iron sand were higher than for a conventional solar stil. The overall efficiency increased in V1, V2 and V3, confirming that the presence of iron sand in a single-basin solar still improved performance. It is recommended to set the water surface level as high or higher above the surface of iron sand.

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