Hourly Thermal Retention and Vapor-Path Relief in a Humidity-Controlled Passive Solar Still

Salwa Din[1,*]

[1] York University, ON, Toronto, Canada.
* Correspondence: salkammd@my.yorku.ca

Abstract: Passive solar stills typically generate most of their distillate later than their solar radiation maxima, but such late day activity is often concealed if the performance is assessed on daily basis or based on water temperature. This study considers a single slope passive solar still operating under an evaporation chamber aspect ratio of 1.53 and relative humidity of 77.5%. The key issue of this study is what hourly values determine the ability to maintain the collection of distillate when the radiation falls, and whether the aspect ratio and the chamber humidity have the same physical basis. The data set consists of ambient temperature, solar radiation, wind velocity, cover temperature, water temperature, basin temperature, hourly distillate production and thermal efficiency from 09:00 to 17:00. The analysis employs temperature differences between basin and cover and water and cover, hourly distillate production normalized to solar radiation, percentage of post-peak generation of distillate, retention of basin-cover difference in the afternoon and normalized trajectory matching hourly yield. The still generated $3.66\,\mathrm{L\,m^{-2}}$ of distillate during the day, having its hourly maximum at 13:00 - $0.61\,\mathrm{L\,h^{-1}\,m^{-2}}$. During the period from 13:00 to 17:00, the solar radiation fell by 46.1%, and the hourly distillate yield by 34.4%, accounting for 70.8% of the daily distillate. The basin-cover temperature difference maintained 93.0% of its daily maximum during the afternoon, and the normalized hourly distillate production in 13:00-17:00 was 1.42 higher than in 10:00-12:00. For the whole day, the correlation coefficient of hourly yield vs. basin-cover difference is 0.870, but for 10:00-17:00 without the point 09:00 it is only 0.594. Physical meaning, therefore, cannot be expressed just by maximum temperature concept. While the main effect of high aspect ratio is increasing of the internal thermal state, lower chamber humidity can increase distillate production despite lower basin and water temperatures.

Keywords: passive solar still; solar desalination; humidity; aspect ratio; distillate yield; temperature separation; vapor transport; transient heat transfer

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1. Introduction

Solar distillation is a significant low complexity technology for generating fresh water in the regions with lack of electrical energy, pressure distillation and qualified maintenance. The passive basin distiller transforms solar radiation heat into evaporation, transfers moisture vapor through the humid enclosure, condenses vapor on the cool glass cover and drains condensate into collection channel. That straightforwardness of operation makes the interest of passive distillation systems for decentralized water purification, however its applicability is limited by the small amount of daily productivity [1,2].

In the seeming simplicity of this apparatus can be hidden the complicated series of coupled events. Solar radiation first heats the absorber and the water layer above it, but the measured distillate appears only after the vapor crossing the enclosure and condensation on the cover. Glass temperature, wind, relative humidity, basin heat capacity are all parameters which change that chain. For this reason, the value of daily productivity is adequate for reporting the service results, but insufficient for understanding of the machine operation. The still producing the same amount of water daily can perform it with the peak during noon, plateau during afternoon or delayed thermal energy release. All these ways give different decisions in designing even if the water amount collected is similar.

Mechanistic interpretation must be able to distinguish the questions concerning the liquid phase and vapor phase. In the case of liquid phase these are the questions about the heat absorption by the basin, the temperature of the water layer sufficient for evaporation and temperature of the cover cooler than the evaporation area. For the vapor phase these questions are about the distance to saturation, vapor easy releasing from the water layer and condensate drain without re-evaporation and clogging of the flow channels. Such questions are typical in solar distillation modelling, but they are often simplified in the manuscripts into single daily values. In this paper the hourly sequence will be kept visible for the interpretation of the time, storage and vapor transportation.

Daily productivity alone is unable to specify the physical reason for still enhancement. The same amount of collected water can appear due to higher absorptance, lower water depth, better insulation, smaller vapor path, cooler cover, better cooling effect of the external wind or lower chamber humidity [3]. The reviews on solar distillation clearly show that the productivity is controlled by interacting climatic, geometric, material and operational parameters rather than by some single temperature or yield value [4,5]. Also the recent reviews on this topic published prior to 2023 point out that the still enhancement must be understood in the context of evaporation, vapor transportation, condensation and thermal energy storage [6,7].

Such distinction is important because there are many examples in solar-still literature of successful passive modification, but not all of them have similar physical origin of the performance improvement. Wicks, fins, sensible heat storage materials, stepped basins, external reflectors, double slope cover and cover cooling techniques are all examples of increased water collection, but these enhancements work through different mechanisms: some of them raise the absorber temperature, other widen the evaporation area, shorten the diffusion distance, decrease the cover temperature or raise the temperature difference in the vapor area [8,9]. Discussion of performance improvement as increase in temperature ignores such difference [10].

Aspects ratio and humidity used in this study are especially good for separate interpretation. Aspect ratio changes the geometry of the evaporation chamber, including the relative height and volume of the vapor area, vapor transport path and the relation between evaporation area and condensation cover. In turn, the humidity is the direct parameter of the vapor state. The saturated chamber can accept less vapor even if the water is heated, while the unsaturated chamber may collect more condensate with lower average water temperature. So the analysis will examine the sequence of measured temperatures and response to the humidity as two related, but not equivalent effects.

Classical thermal analysis of basin stills starts with the coupled heat and mass transfer between the water surface and the glass cover. The formulae of Dunkle and following development correlate the evaporation with the temperature and vapor pressure difference in the enclosure [11,12]. The humid air properties are critical in such calculations as the density, diffusivity, vapor fraction and saturation pressure vary by temperature and relative humidity [13]. Such formulas are essential for modelling, but they do not eliminate the necessity of interpretation of the hourly sequence of the measurements. The passive still consists of water, basin material, glass cover, insulation and humid air with different thermal time response.

For this reason, the hourly sequence is not a secondary feature, but the observation of the basic physics. The basin can continue to release the heat after the solar energy input becomes less, while the glass cover can be hot enough to hinder condensation even when the water temperature is high. The wind helps by cooling the external cover, but increases the losses from the system. The relative humidity can reduce the evaporation rate when the chamber is approaching the saturation, but the same chamber may start collecting more water if the vapor is removed or the cooler cover conditions are achieved. These coupled effects explain the inability of the single correlation with radiation or water temperature for the diagnosis of the passive stills.

Transience is the important property of single slope solar stills. Early digital simulations showed that the water depth, cover temperature, insulation, wind and daily radiation variations influence the transient response of distillation systems [14]. Following experiments confirmed that the brine depth, enclosure height, chamber geometry, cover arrangement and basin configuration strongly influence the temperature and productivity of the system [15,16]. The daily total must be interpreted in conjunction with the transient response of the radiation, basin heating, water heating, cover warming and distillate collection [17,18].

The present analysis follows that transient perspective and examines the time of reaching by the measured quantities the most important state. The time of radiation maximum specifies the external forcing. The time of basin temperature maximum corresponds to the maximum stored thermal energy. The time of maximum water temperature indicates the strongest heating of the liquid domain, while the cover temperature corresponds to the condensation limit. The sequence of collected distillate shows the dependence on solar input or stored thermal energy. The chronological interpretation of these parameters eliminates the incorrect assumption that all maxima are simultaneous.

Geometry and humidity act on different parts of the process. The increasing chamber aspect ratio changes the volume of the enclosure, vapor travel distance, buoyancy circulation and thermal relations between the evaporating water and the condensing cover. Reduction of the relative humidity influences the vapor phase by changing the saturation state of the air-vapor mixture and resistance to the vapor leaving the water surface. The publication of experimental data on the passive single slope still with varying chamber aspect ratio and controlled humidity provides the hourly data appropriate for separation of these effects [19,20].

The current paper addresses the specific physical question: at what times of measuring quantities does the still continue to produce after the radiation has started decreasing, and does the aspect ratio and humidity produce this effect through the same mechanism? The answer is obtained from the measured component temperatures, radiation, wind speed, hourly yield and efficiency. The paper concentrates on the measured values: $982\,\mathrm{W/m^2}$ radiation maximum, $0.61\,\mathrm{L\,h^{-1}\,m^{-2}}$ yield maximum, $3.66\,\mathrm{L\,m^{-2}}$ daily yield and the afternoon separation of basin and cover temperatures.

The research question is deliberately narrow compared to the general comparative analysis of the solar still configurations. It is focused on the way of interpreting the single operating day when the still continues to produce after the radiation maximum. The approach gives priority to the measured variables: component temperatures, hourly yield, radiation, wind speed and chamber humidity. The daily output is not taken as the single measure of the performance, but as the final result of the hourly thermal and vapor sequence.

2. Measurement Data and Calculated Variables

2.1. Hourly operational data

In this study, a passive still is analyzed which is characterized by being a single slope, single basin, tested under controlled humidity in the chamber and a variable aspect ratio of evaporation chamber [20]. One specific case studied in this paper has aspect ratio of $AR = 1.53$ and chamber relative humidity of $\phi = 77.5\%$. Measured variables in this case include ambient temperature T_a, solar irradiation I_s, wind speed V, temperature of glass cover T_g, water temperature T_w, basin temperature T_b, distillate production rate per hour $\dot{m}$, and thermal efficiency η.

This particular case is chosen since it has complete data on daytime and all measured variables are available for this case. Also, the aspect ratio of 1.53 can be treated as moderate chamber geometry, rather than some extremely large one and relative humidity of 77.5 % puts the still below saturated operation, but still in a humid enclosure. This allows the data to be used for studying whether afternoon response is driven by thermal storage alone or also vapor side conditions are to be taken into account. The order of variables remained the same as in the original hourly measurements.

The photograph of the setup in Figure 1 shows the locations at which the measurement was made during all of the calculations. The basin, water layer, angled glass cover, chamber relative humidity display, radiation source, exit, and collection cylinder are indicated in the same order that they appear physically along the heat and vapor route analyzed through the calculations. It is important to note that the quantities being measured cannot be interchanged in the equation: T_b measures the heat-trapping surface of the still, T_w measures the evaporating water, and T_g measures the condensing interface.

Figure 1. Instrumented solar still.

These locations of the instruments determine the meaning of each calculation that is performed. An expression of the difference between T_b and T_g, for example, is not an expression of merely the numerical difference between the two numbers but represents the thermal relationship between the absorber area and the condensing interface. Similarly, the difference between T_w and T_g is more directly related to the evaporation-condensation relationship at the water interface and glass cover. External cooling is described by the ambient temperature and wind velocity, while the chamber humidity represents the proximity of vapor saturation within the chamber.

Table 1. Hourly operating values.

Time (h)	T_a (°C)	I_s (W/m^2)	V (m/s)	T_g (°C)	T_w (°C)	T_b (°C)	$\dot{m}$ (L h^{-1} m^{-2})	η (%)
9	22.7	545	1.34	23.8	21.0	23.5	0.00	0.0
10	23.1	665	2.11	35.7	40.1	41.4	0.28	18.2
11	25.2	765	2.67	43.8	49.3	50.5	0.36	26.5
12	26.5	870	2.22	52.1	60.9	62.0	0.43	25.4
13	29.2	982	1.61	57.4	64.3	66.6	0.61	24.4
14	32.9	943	3.30	59.4	67.5	69.9	0.58	22.9
15	31.4	865	4.23	59.8	68.2	69.6	0.52	22.4
16	30.1	701	4.11	54.7	64.3	64.5	0.48	26.1
17	29.8	529	5.78	45.5	56.8	55.0	0.40	28.8

Figure 2 visually records the nine hourly states shown in Table 1. The initial cylinder is empty since there was no distillate collected at 09:00 while the cylinder at 13:00 shows the highest hourly production. The remaining cylinders stay visibly full even after radiation decreases and predict post-peak holding as discussed in the Results section.

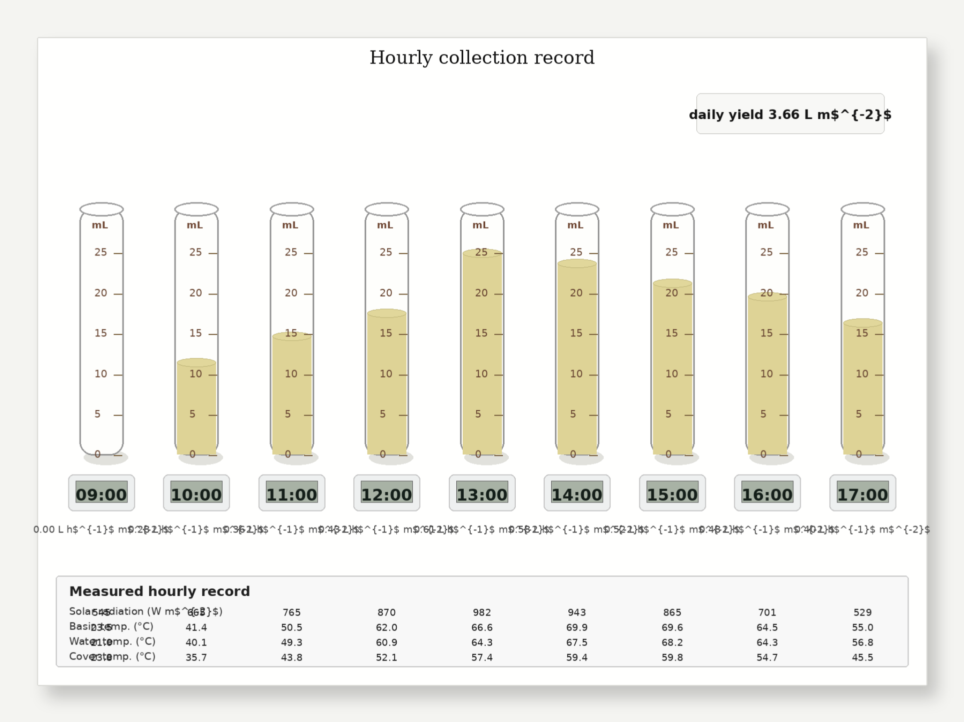


Figure 2. Hourly collection record.

The first hour is a case of heating process: radiation is 545 W/m^2 while the collected distillate is zero and the temperature of the water is lower than that of the glass cover. For 10:00 and further hours the temperature of the water and basin is higher than that of the cover and the still makes condensate. Hence, the 09:00 reading is part of the daily record but not part of the productive transfer regime.

The difference between heating and productive regimes is critical when it comes to regression analysis. Including 09:00 gives an opportunity to plot the curve showing the entire transition from the cool non-productive state to the producing still. Not including it helps to see whether the same pattern works in the case when evaporation and condensation started. Both records help but ask different questions. The full record checks if the temperature difference can be used as an indicator of the start of distillation while the productive-hours record checks if it can explain the changes that occurred after the still became productive.

2.2. Temperature and production diagnostics

The calculations involve two physically measured temperature differences. The first one is The analytical method has been intentionally made easy to understand. No physically not-measured heat transfer coefficient has been calibrated, nor has any hidden parameter been used to make temperatures match production. Rather, measured variables have been transformed into physically interpretable indicators. This approach is appropriate for a short-hourly data set, since it prevents overfitting but extracts the main features of the process.

$$\Delta T_{bc} = T_b - T_g, \tag{1}$$

and the water-cover separation is

$$\Delta T_{wc} = T_w - T_g. \tag{2}$$

The first one is an indicator of temperature difference between the heat-retentive basin and the condensing cover side; the second is a temperature differential between the fluid and the cover. Distillate production rate per hour is additionally normalized with respect to solar radiation at the same time period:

$$P_s = \frac{\dot{m}}{I_s}. \tag{3}$$

It is not an energy efficiency ratio. Its purpose is to give a water-per-radiation hourly performance index for the identification of still ability to produce distillate under reduced levels of incident radiation. A large value of P_s later during the day should not be interpreted as an energy imbalance because it means that the heat supply for the current hour of operation comes from a combination of present irradiance and stored heat in the basin-water system. Therefore, the index is more meaningful when it is evaluated in conjunction with temperature differentials and not separately as a measure of performance.

The agreement between trajectories of any measured parameter x and hourly yield is assessed using the following equation after min-max normalization:

$$A_x = \frac{1}{N}\sum_{i=1}^{N}[1 - |\hat{x}_i - \hat{m}_i|], \tag{4}$$

where $\hat{x}_i$ is the normalized time trajectory of x, $\hat{m}_i$ is the normalized time trajectory of hourly yield, and $N = 9$. The value serves only to quantify the similarity of trajectories. It is not a heat transfer coefficient and it cannot be considered causal evidence. For example, a variable could have a high agreement score with hourly yield simply because both variables rise and drop together with no other connections. Basin temperature could have the alignment with yield since it stores heat; the cover temperature could have the alignment since it changes in response to the same irradiance as yield.

Table 2. Calculated hourly values.

Time (h)	ΔT_{wc} (°C)	ΔT_{bc} (°C)	$P_s \times 10^4$ (L/h/m^2/W)	$\dot{m}/\Delta T_{wc}$ (L h^{-1} m^{-2} °C^{-1})
9	-2.8	-0.3	0.00	–
10	4.4	5.7	4.21	0.064
11	5.5	6.7	4.71	0.065
12	8.8	9.9	4.94	0.049
13	6.9	9.2	6.21	0.088
14	8.1	10.5	6.15	0.072
15	8.4	9.8	6.01	0.062
16	9.6	9.8	6.85	0.050
17	11.3	9.5	7.56	0.035

The obtained values differentiate between two phenomena that are quite easily confused. In particular, the water cover separation attains its peak at 17:00, well after the peak of the hourly yield that occurs at 13:00. On the other hand, the basin cover separation stays close to 10 °C during the whole afternoon period. Late day productivity is thus not just dependent on the maximum possible liquid-cover temperature difference; it also relies on the heat and vapor removal capabilities present at that time.

At 09:00, the negative values also have a physical meaning. At this hour, the cover is hotter than the water, and thus neither water cover nor basin cover separation can be interpreted in terms of evaporation and condensation. First, the still needs to change this situation and heat the water and basin components. From 10:00 on, the separations turn positive, and the hourly yield becomes nonzero. Thus, the calculated values not only give the magnitudes of the temperature difference but also the moment when the still acquires a productive thermal setup.

2.3. Aspect ratio and humidity evidence

There are two cross-condition comparisons in the conducted measurements that allow differentiating between mechanisms. Increasing the aspect ratio from 1.02 to 2.30 leads to an increase of component temperatures. Lowering the humidity of the chamber compared to the saturated state leads to decreasing basin and water temperatures on average but increasing yield.

The data in Table 3 rules out any simple temperature explanation for these differences. While a hotter basin will facilitate evaporation, the humidity difference indicates that removal of vapor can take precedence over the mean liquid temperature. Therefore, the control variable must relate to what the control itself affects: heat stored, vapor transport, or condensation.

The distinction between the two mechanisms also enhances the utility of the hourly validation data. In addition to the effect of higher humidity at 77.5%, the lower humidity case at 62.4% shows that an even lower-humidity chamber may yield high production in a day at the same aspect ratio, despite the different thermal profile. Combining these two cases provides a richer understanding of the data than just repeating daily yields. Which mechanism is changed by geometry? Which one by vapor state control?

Table 3. Cross-condition evidence.

Change in operation	Measured effect	Physical reading
Aspect ratio increased from 1.02 to 2.30	Cover temperature increased by 5.6%; basin and water temperatures increased by 9.2% and 11.3%, respectively.	Larger chamber aspect ratio strengthens the internal thermal state and changes the characteristic vapor path.
Humidity reduced relative to saturated operation	Basin and water temperatures decreased by 8.5% and 3.2%, respectively, while yield increased by 17.7%.	Lower humidity reduces vapor-side resistance; higher yield does not require higher average liquid-domain temperature.
Operation at $\phi = 62.4\%$ and $AR = 1.53$	Daily output reached $3.49\,\mathrm{kg/m^2/d}$ with thermal efficiency of 34.2%.	Moderate geometry can produce strong daily output when the chamber is less saturated.

3. Results

3.1. Hourly timing of heat input and distillate collection

The operating day provided $3.66\,\mathrm{L\,m^{-2}}$ in the period from 09:00 to 17:00. The maximum radiation, $982\,\mathrm{W/m^2}$, was reached at 13:00. It corresponds to the maximum hourly yield of $0.61\,\mathrm{L\,h^{-1}\,m^{-2}}$. Temperatures of the component reached their peak values later: the basin attained 69.9 °C at 14:00, while the water and cover attained 68.2 °C and 59.8 °C, respectively, at 15:00.

Timing diagram in Figure 3 shows the maximum radiation and maximum hourly collection at 13:00 while the materials achieve their maximum temperatures later: 14:00 for the basin and 15:00 for the water and glass cover. Such behavior is a natural feature of transient solar-still operation where the thermal inertia of water depth and material heat capacity delays the response of the system to weather changes [14,21]. It explains why the afternoon time cannot be considered just another low energy input period.

The described sequence makes clear why there is no necessity for the maximum yield to coincide with maximum water temperature. At 13:00, the maximum radiation is achieved and the still accumulates enough energy for evaporation. At 14:00 and 15:00, the materials inside the device get warmer, but the radiation decreases, and the cover is warmer, too. The higher temperature of the cover may decrease the efficiency of condensation despite high water temperature. Therefore, the actual operating condition is the combination of radiation level, accumulated energy, chamber vapor and cover cooling.

Such timing has practical importance for testing the still. Reporting just 15:00 water temperature, the reader would think that the maximum production is achieved at that hour. Reporting just maximum radiation, one would fail to see the delayed reaction of the basin and water. Timing and value together provide information about the memory effect: energy received by the still before and at noon influences the process of water collection in the later afternoon. Memory effect is the key characteristic of passive systems with substantial water and basin heat capacity.

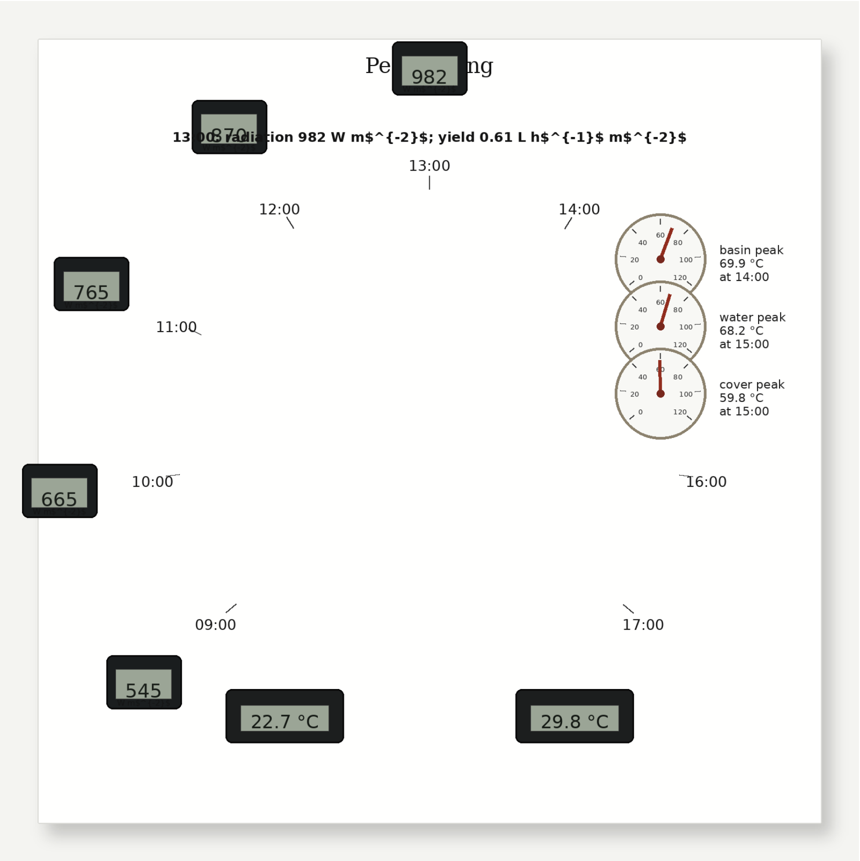


Figure 3. Thermal-lag timing.

Between 13:00 and 17:00, the still collected 2.59 L m^{-2}, which is 70.8% of the daily total. Even excluding the peak hour at 13:00, the 14:00–17:00 period provided 1.98 L m^{-2} which is 54.1% of the daily total. Thus, the still managed to preserve its productivity after the moment when the external energy input started decreasing.

The contribution of the post-peak period is sufficient to change the understanding of daily operation of the still. In the morning between 10:00 and 12:00, the thermal state of the device is established and it collects 1.07 L m^{-2}. Just in one peak hour at 13:00, the still collects 0.61 L m^{-2}. Then, in the late afternoon between 14:00 and 17:00, the still collects almost twice as much water as in the morning period.

3.2. Basin-cover separation and hourly yield

Basin-cover separation increases from -0.3 °C at 09:00 to 9.9 °C at 12:00 and remains in the range of 9.2 °C–10.5 °C between 13:00 and 17:00. Water-cover separation demonstrates different behavior and reaches 11.3 °C at 17:00 although hourly yield decreased to 0.40 L h^{-1} m^{-2}. Basin-cover separation and water-cover separation thus are separate parts of the process rather than interchangeable parameters.

Plotted sheet on Figure 4 divides start-up from production process. Yield increases between 09:00 and 13:00 together with basin-cover separation; after 13:00, yield starts to decrease slowly despite high basin-cover separation. Therefore, basin-cover separation can be treated as a good daily-state parameter but cannot serve as an hourly transfer law.

The curve should be interpreted as a state path rather than a linear relationship. The first part of the curve represents a shift from inactive to productive states with basin becoming warmer than the cover. The middle point at 13:00 denotes the hour at which sufficient separation coincides with maximum radiation. The last part of the curve stays within the high-separation region and descends in yield because some other factors do not become favorable enough. Such interpretation reveals much more information than just the value of correlation.

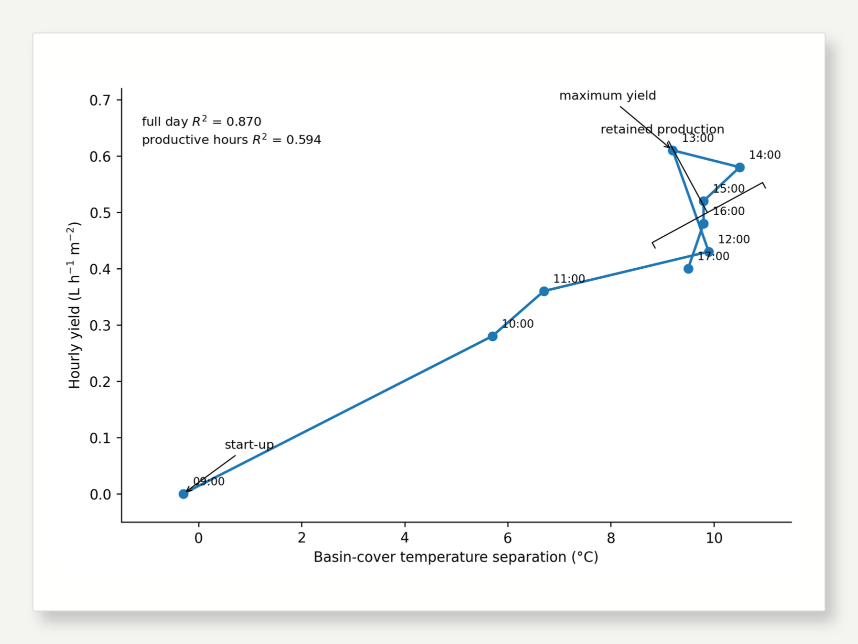


Figure 4. Separation-yield path.

Also, the post-peak section explains why the same basin-cover separation corresponds to different yields. From 13:00 to 17:00, separation stays within a small range, but hourly yield decreases from 0.61 L h^{-1} m^{-2} to 0.40 L h^{-1} m^{-2}. It means that thermal potential of the still remains unchanged, but its conversion into water decreases. Possible causes may include warm glass cover, external wind influence, decreased radiation and difficulties in vapor transfer through the humid chamber.

For the nine-hour data set, the least squares relation between hourly yield and basin-cover separation is

$$\dot{m} = 0.0499\Delta T_{bc} + 0.0143, \tag{5}$$

with $R^2 = 0.870$. Excluding start-up 09:00 point, this relation is expressed as

$$\dot{m} = 0.0502\Delta T_{bc} + 0.0117, \tag{6}$$

with $R^2 = 0.594$. Lower correlation coefficient in productive hours proves that after start-up, along with basin-cover separation, other factors such as vapor saturation, cover condensation, heat loss due to wind and decreasing radiation influence yield. This fact allows not to overestimate the regression. High value of R^2 for full day data results partially from the existence of the start-up point with zero yield and zero basin-cover separation. Without this point, the remaining eight points have a smaller range of basin-cover separation and yield variations are determined by additional terms.

3.3. Afternoon retention during solar radiation decline

The solar radiation declines from $982\,\mathrm{W/m^2}$ at 13:00 to $529\,\mathrm{W/m^2}$ at 17:00, that is 46.1%. At the same time, the hourly distillate yield decreases from $0.61\,\mathrm{L\,h^{-1}\,m^{-2}}$ to $0.40\,\mathrm{L\,h^{-1}\,m^{-2}}$, or 34.4%, which means less pronounced decrease.

The smaller decrease of the distillation output shows the presence of partial buffer in the form of the energy stored within the system and basin-cover separation.

As can be seen in Figure 5, there is difference between the values of the solar radiation and corresponding yields, which allows making the conclusion about partial buffer present in the still. During 13:00–17:00 hours, the mean basin-cover separation is 9.76 °C, which constitutes 93.0% of the maximum daily value 10.5 °C. The solar-normalized distillate production during the period 13:00–17:00 hours is 1.42 times larger than during 10:00–12:00 hours. It does not mean that the later period produces more water in absolute numbers than the peak period, but rather that the still produces more water per unit of simultaneous radiation in view of the developed thermal state of the system.

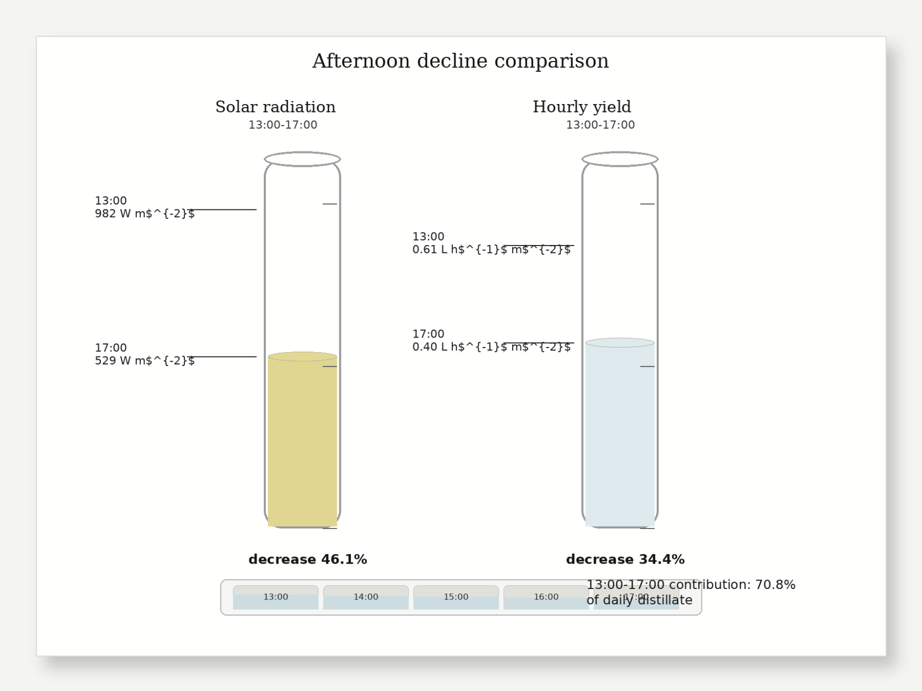


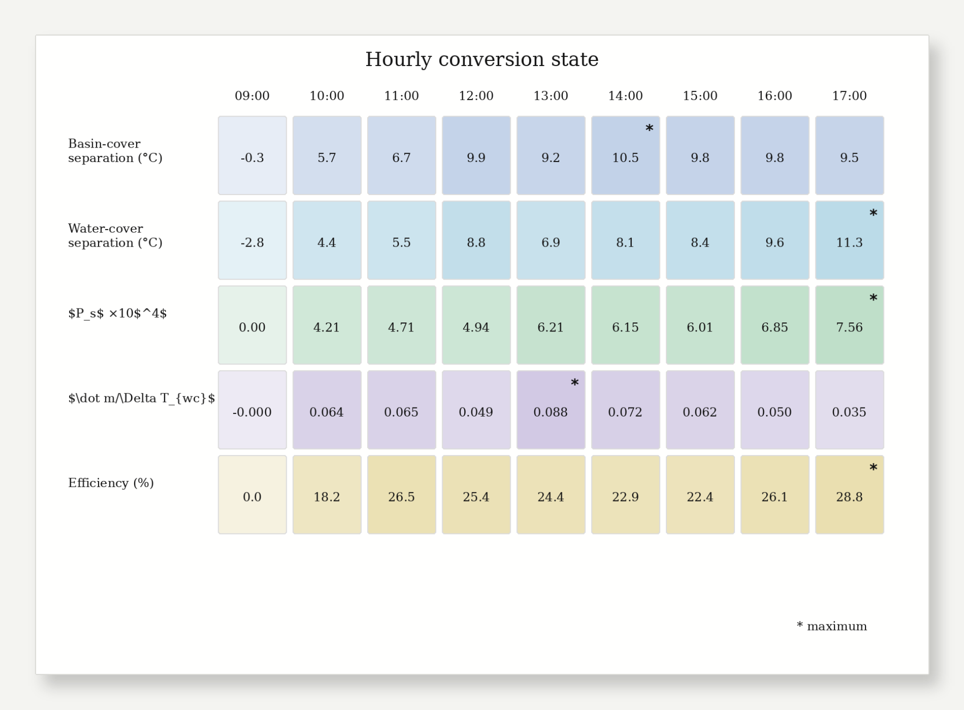
Figure 5. Comparison of afternoon radiation decline and its impact on the hourly yield of distilled water.

It is convenient to make the comparison of the two declines because of their different slopes. As can be seen, while radiation loses nearly half of the value at 13:00 by 17:00 hours, the hourly yield loses only one-third of it. If the process were entirely controlled by instantaneous radiation, then the decline would be steeper. Hence, the slower yield decline shows the presence of buffer in the system in the form of the stored energy, which still drives evaporation. At the same time, the yield does decline, which means that the stored energy is not sufficient to provide the maximal level. So, the response of the system to the afternoon changes is a buffered decline, not the plateau.

The maintenance of the sustained basin-cover separation provides such buffer. During 13:00–17:00 hours, the separation never falls below 9.2 °C despite of the substantial decline of the solar

This ratio reaches its maximum value of $0.088\,\mathrm{L\,h^{-1}\,m^{-2}\,{}^{\circ}C^{-1}}$ at 13:00 hours. By 17:00, this value drops down to $0.035\,\mathrm{L\,h^{-1}\,m^{-2}\,{}^{\circ}C^{-1}}$, although the water-cover separation reaches its largest value. The largest temperature difference between liquid and cover is thus not the hour with the most favorable conversion of heat into distillate collection.

The mosaic shown in Figure 6 presents the calculated hourly indicators in parallel view. Maximum water-cover separation is achieved at 17:00 hours, while maximum output per unit water-cover separation is at 13:00 hours. The same chart reveals that the normalized production with respect to the solar irradiation improves late in the afternoon, despite a decrease in the absolute value of hourly yield. This information indicates that the still moves into the heat storage state, rather than acting on instantaneous radiation only.



Hourly conversion state

	09:00	10:00	11:00	12:00	13:00	14:00	15:00	16:00	17:00
Basin-cover separation (°C)	-0.3	5.7	6.7	9.9	9.2	* 10.5	9.8	9.8	9.5
Water-cover separation (°C)	-2.8	4.4	5.5	8.8	6.9	8.1	8.4	9.6	* 11.3
P_s ×10^4	0.00	4.21	4.71	4.94	6.21	6.15	6.01	6.85	* 7.56
$\dot m/\Delta T_{wc}$	-0.000	0.064	0.065	0.049	* 0.088	0.072	0.062	0.050	0.035
Efficiency (%)	0.0	18.2	26.5	25.4	24.4	22.9	22.4	26.1	* 28.8

* maximum

Figure 6. Hourly conversion state.

The comparison between the two normalized indicators is especially revealing in this case. The solar-normalized production rises late in the afternoon, since the denominator (solar irradiation) falls faster than the numerator (collected water). Output per unit water-cover separation drops, because the increase of the temperature difference at the liquid-cover pair does not result in proportional increase of the condensate collection. In combination, these two facts indicate that the still becomes thermally ready late in the afternoon, but the efficiency of the heat transfer through evaporation and condensation channel drops.

Visual grouping helps to differentiate high value cells from operating conditions. The maximum in the row of calculated indicators is not necessarily the best indicator of high yield. While 17:00 water-cover separation is the largest one, 13:00 hour is associated with maximum hourly yield. A useful operating condition is thus a combination of several factors: high solar irradiation, ready heat in the basin, positive water-cover separation and sufficient condensate collection.

3.4. Dissimilar effects of aspect ratio and humidity

Increases in aspect ratio and humidity create dissimilar physical signatures. Increasing aspect ratio causes higher cover, basin, and water temperatures, whereas reducing humidity causes higher yield even with lower basin and water temperatures. The former is a thermal retention effect, the latter is a vapor path improvement effect.

The response plate in Figure 7 highlights the difference between these two factors. The aspect ratio effect is a positive one on all measured component temperatures. The humidity effect is a negative one on basin and water temperatures but a positive one on yield. It is understandable from a physical perspective that a less saturated chamber can absorb extra vapor easier, thus facilitating the condensation process despite average lower liquid-domain temperature [12,13].

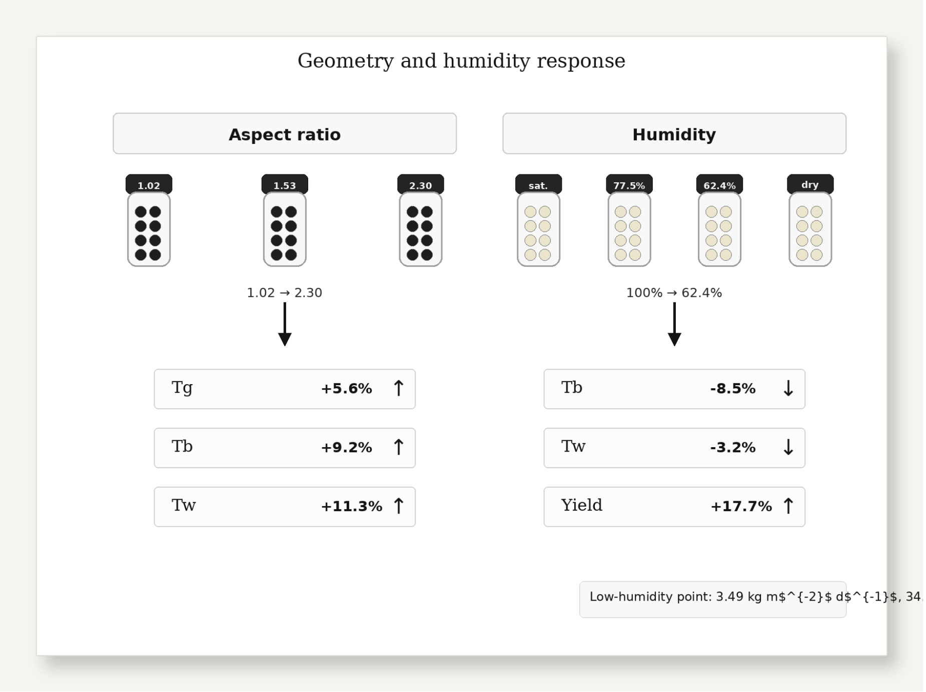


Figure 7. Geometry-humidity response.

This finding is important because it allows us to distinguish the temperature rise effect from the productivity increase effect. Increase in aspect ratio from 1.02 to 2.30 causes an increase in component temperatures. Lowering humidity behaves differently. Despite lower basin and water average temperatures, yield rises by 17.7%. The most straightforward interpretation is that vapor path restriction reduces, and the process of evaporation from the water surface is facilitated, as well as the condensation process.

In this context, a design implication is that there are two paths to reach the daily yield goal. One path is to improve the thermal retention effect and increase component temperatures. Another path is to reduce vapor path restriction and improve mass transfer at a certain level of temperature. A still that implements both methods should ensure sufficient basin heat while avoiding the excessive saturation of the chamber. The differentiation between these two cases can be used in passive designs because an increase in heat without better vapor removal may cause increase in temperature but not in collected water.

A design implication is that the operating point characterized by $\phi = 62.4\%$ and $AR = 1.53$ achieved $3.49\,\mathrm{kg/m^2/d}$ and 34.2% efficiency. It means that it is close to the total of $3.66\,\mathrm{L\,m^{-2}}$ achieved on the validation day. The comparison supports the design interpretation where chamber humidity and geometry are independent factors rather than a single enhancement.

The comparison shows that the humidity is an important parameter that should be actually measured. A passive still is often considered to be a humid sealed chamber, however, its degree of saturation can be different depending on temperature, condensation, air leakage, airflow, and vapor removal from the chamber outlet. At a lower degree of humidity, a chamber can maintain a larger vapor pressure gradient from the water surface to the air space. Without the actual measurement of the humidity value, a higher yield can be erroneously attributed to geometric or radiation improvements only.

3.5. Agreement between trajectories and hourly yield

The calculation of normalized trajectory agreement selects the variables which trajectories match those of the hourly yield the most. Basin temperature has the highest agreement index, followed by glass cover temperature and water temperature. Although solar radiation is the source of energy in this still, its curve doesn't correspond as much to yield as internal component temperature trajectories due to the delay and persistence properties.

From Figure 8, it is clear that the variables of basin temperature ($A_x = 0.935$), glass cover temperature ($A_x = 0.931$) and water temperature ($A_x = 0.922$) align best with the hourly yield trajectory. Next in line come basin-cover temperature difference ($A_x = 0.884$) and water-cover temperature difference ($A_x = 0.872$). Wind velocity ($A_x = 0.640$) has significantly lower index. Despite having an effect on external cooling of glass cover, wind is not the organizing factor for the hourly yield pattern like the internal temperature sequence in this particular record.

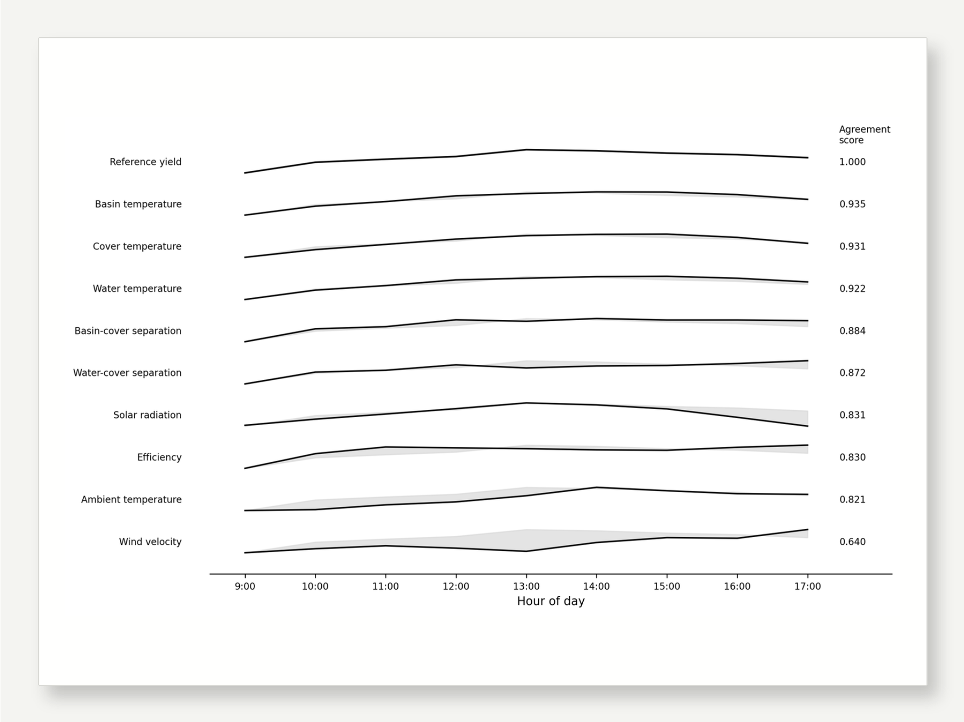


Figure 8. Alignment of trajectories to yield.

The large alignment index of glass cover temperature might seem to be against the expectations since a lower temperature of glass cover is desirable for condensation. However, the reason behind it is that temperature of cover increases due to solar radiation as well and the shape of its hourly trajectory follows the thermal development of the still. Similar interpretation holds for basin and water temperature. Their high agreement indices mean that their trajectories match the yield day pattern and not that any of these variables determines the yield.

In this particular record, wind velocity has significantly lower agreement index than other variables. However, this doesn't mean that it is irrelevant. It influences the external heat transfer coefficient and condensation rate through the cooling of the glass cover. Nevertheless, in this particular record, wind velocity has significant increase later in the day when yield starts decreasing. Thus, its trajectory differs from the yield one despite the possible effect on heat balance. The main use of agreement index is to determine which measured sequences have similar shape to the production one and which need different explanation.

4. Discussion

4.1. Physical answer to the research question

Results suggest an answer based on two physical zones. In the hourly validation experiment, yield retention results from heat storage and separation between the basin and cover. Over varying humidity levels, there can be increased production without higher basin and water temperatures, indicating the existence of an additional vapor-side resistance limitation. The still retains production capability due to heat retention and vapor relief.

Figure 9 illustrates the physical interpretation of the apparatus in two regions according to the measurements performed during this experiment. The basin region reflects the retained heat and peak-to-peak contributions, whereas the sloped cover and outlet are associated with vapor removal and distillate recovery. The figure is presented in the discussion because it summarizes the results provided in Tables 1–3 and Figures 1–8.

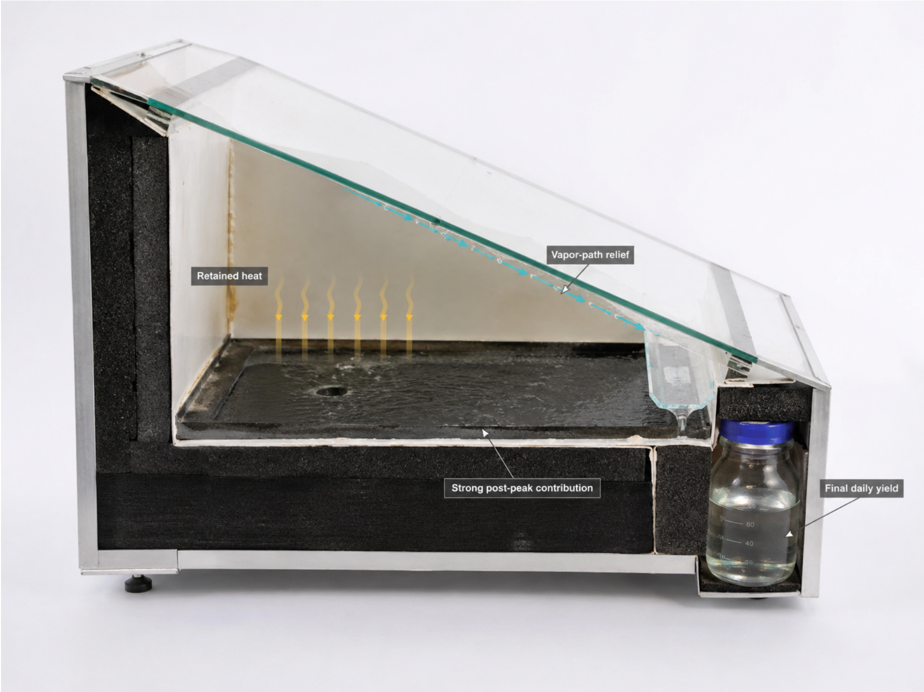


Figure 9. Heat-vapor operating state.

This interpretation can be useful for future evaluations of any apparatus design changes. For instance, a design modification that is located in the basin should be evaluated in terms of its effect on heat retention, water temperature, and basin-cover separation. Similarly, a modification made in the vapor region should be assessed according to its impact on humidity, vapor removal, and condensation recovery. Finally, a cover cooling modification should be evaluated in terms of lowering the condensing temperature boundary without reducing the useful heat content of the water.

In contrast with the maximum-temperature explanation, higher water temperature can increase the vapor pressure, but the maximum separation occurs at 17:00, and not at the hour of maximum production. The still has favorable water to cover temperature separation, but low energy input and low $\dot{m}/\Delta T_{wc}$ ratio. The most productive hour is characterized by the combination of effective heat retention, sufficient solar input, and vapor removal.

This interpretation confirms the principles of classical solar still theory, but reinterprets their reporting. Maximum-temperature relations allow to understand the importance of temperature differences and vapor pressure difference [11]. Transient simulations explain the delay of basin and water responses to radiation [14]. Humid air properties help to assess the role of relative humidity in vapor transport [13]. The current approach returns all these aspects to the hourly measurement records: the most productive hour corresponds to the overlap of thermal and vapor conditions, but not to the maximum value of any temperature.

Aspect ratio change affects mainly the thermal side of the still. The observed changes of 5.6% in cover temperature, 9.2% in basin temperature, and 11.3% in water temperature confirm the influence of geometry on the stored-energy conditions in the still. The reduction of humidity changes the other limitation: yield improvement in case of decreasing average temperatures of the liquid domains. Separation of the two effects prevents the misunderstanding that increased production corresponds to the higher temperature of the basin only.

The same separation can help to plan future experiments on apparatus design modification. If the aspect ratio is varied, the analysis should include the change in component temperatures and temperature separations for the whole day period. If humidity and/or ventilation are changed, the analysis should consider relative humidity, vapor removal conditions, and yield per unit of temperature separation. The analysis of the interaction of these effects should involve evaluation of geometry modifications at decreased humidity. Such reports will enhance the reproducibility of passive still comparison studies.

4.2. Implications for reporting on solar stills

While daily yield is required, it is insufficient for providing an explanation for the functioning of a passive still. Instead, an informative report will include the maximum radiation hour, peak times for basin and water temperatures, basin-cover distance, water-cover distance, post-peak yield fraction, and radiation-normalized yield. These parameters are computed on the basis of standard hourly measurements and provide information about the causes of higher productivity in terms of either heat accumulation, cover cooling, vapor escape, or their combination.

This strategy is also relevant when comparing simple basin modifications with more advanced passive systems. Several previous literature surveys showed that fins, wicks, stepped basins, reflectors, double basins, and auxiliary collectors could improve production [8–10]. Mechanisms behind each modification could be different. A fin increases heat transfer area, a thin layer of water decreases thermal inertia, a reflector increases radiation energy, and low humidity decreases vapor resistance. Information about the exact cause of yield improvement will be lost by reporting daily yield only.

For scientific journals, however, the minimum time-resolved set of data required is not large. The hourly data table should contain radiation, ambient temperature, wind speed, basin temperature, water temperature, cover temperature, yield, and efficiency. The second data table should contain at least basin-cover distance, water-cover distance, and radiation-normalized yield parameter. All these parameters require no additional measuring devices, and they enable a reviewer to make sure of thermal plausibility of the reported results, consistency of yield peak with temperature records, and possible effect of the chamber state on vapor transport.

Visual material should follow the same principle. Apparatus pictures should mark locations of the measurements; timing diagrams should visualize the sequence of peaks; calculation diagrams should illustrate the changes in indicators throughout the day; and final summary graphs should relate measurement data to physics. Such diagrams are helpful in preventing a frequent weakness of solar-still articles: presentation of pictures, yield diagram, and tables independently of each other without showing the relation between them leading to the final conclusion.

Therefore, practical implications of the present results are straightforward. Aspect ratio should be chosen so that internal thermal conditions remain good enough, while the chamber humidity should be controlled or reduced in order to prevent vapor-side saturation. Higher temperature does not necessarily mean higher productivity and lower liquid temperature could still provide higher yield if vapor side is better.

In case of field application of a solar still, construction details should be estimated from both the points of view of heat retention and vapor handling. Heat insulation, absorptivity of the basin, and water depth affect post-peak productivity, while the angle of the cover, vapor volume, and outlet design affect ability to collect the vapor. The present measurements indicate that optimal operation condition is not necessarily the highest temperature condition; it is the condition of balance between retained heat and vapor collection.

4.3. Limitations of the calculation

The data is an hourly one that does not incorporate local vapor velocity, spatial humidity gradient, thickness of condensation film, or high frequency of cover temperature variation. Trajectory agreement parameter is merely descriptive, showing similarity in shape of curves, but not their causal correlation. More sophisticated modeling should consider directly calculated values of heat transfer by evaporation, convection, and radiation, as well as chamber humidity profiling and condensation film observations.

Despite those limitations, the calculation proves to be valuable as it takes values commonly obtained during testing of solar stills: radiation, ambient temperature, wind speed, component temperatures, yield, and efficiency. Those values are converted into physically meaningful information on time of delay, stored heat, and conversion into condensate while complying with established principles of transient modeling [14,19,22].

Further research should take into account clear and cloudy days, various water depths, and continuous measurement of controlled humidity levels. Higher frequency record should allow more accurate estimation of delay between radiation, component temperatures, and appearance of condensate. Chamber humidity mapping should give a clear answer on relief of vapor pathway being uniform or concentrated in the vicinity of outlet and cover.

5. Conclusions

This paper has investigated the nature of the hourly operating states explaining long-term distillate collection in a humidity-controlled passive solar still and whether aspect ratio and chamber humidity operate via the same mechanism. The hourly record reveals that the answer is not a single parameter effect on temperature. Afternoon yield is maintained due to retention of the internal thermal state of the still, while the humidity comparison indicates that vapor-side resistance can control yield independent of mean basin and water temperatures.

A total of $3.66\,\mathrm{L\,m^{-2}}$ distillate was harvested between 09:00 and 17:00. The peak radiation level and peak hourly distillate yield were at 13:00, while the basin temperature and water/cover temperature peaks occurred at 14:00 and 15:00, respectively. Although the radiation level declined by 46.1%, 70.8% of daily distillate was generated during 13:00–17:00 period. Mean basin-cover temperature separation for this period was $9.76\,^{\circ}\mathrm{C}$, which corresponded to 93.0% of the daily peak.

There is a good correlation between hourly distillate yield and basin-cover separation ($R^2 = 0.870$) over the entire set of hourly data points, but a relatively poor one ($R^2 = 0.594$) after the non-productive 09:00 point has been eliminated from the set. The change in R^2 indicates that basin-cover temperature separation describes the transition from start-up to production mode well, but it does not describe completely the distillate yield beyond the start-up transition stage. Vapor saturation, cover condensation, losses due to wind effects and reduced solar energy level are also important here.

Aspect ratio and humidity should be treated as separate design parameters. Increase in aspect ratio results in higher temperatures in the still interior, while reduction of chamber humidity can enhance distillate yield even with decreased basin and water temperatures. The best description of the still performance thus consists of the behavior of the stored heat, water-to-cover and basin-to-cover temperature separation, chamber humidity and distillate collection. Future tests of passive solar stills should present these hourly data along with the distillate yield, allowing for physical identification of the productive mechanism as opposed to its assumption. The most straight forward answer to the research question can be stated as follows. Output of the still is maintained in spite of decreasing radiation due to heat storage and maintenance of the large basin-cover temperature separation in the afternoon hours. Aspect ratio affects the distillate yield mainly by changing the internal thermal state of the still, while chamber humidity affects the yield through a different mechanism by changing the vapor-side resistance.

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