Desalination and Water Treatment
www.deswater.com

doi: 10.5004/dwt.2023.29673

298 (2023) 12–22
June

Effects of varying weather parameters on solar still performance

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Received 18 February 2023; Accepted 9 June 2023

ABSTRACT

This study presents an empirical model based on experimental results of a simple single-slope conventional solar still's daily yield of distilled water, productivity, and thermal efficiency. The model assumes that the still efficiency can be factored as a function of three independent weather parameters beside solar radiation: atmospheric temperature, wind speed, and dew point. The effect of the latter parameter has seldom been studied. Correlation analysis showed that relative humidity and atmospheric pressure are dependent on those three, and their effects on still performance are only signatures of the three independent weather variables. Hence, they are not included in the modeling. The model predicts that temperature, dew point temperature, and wind speed have a percentage effect of 73.5%, 12.2%, and 14.3%, respectively, on still efficiency. The experiment was conducted over a seven-week period from last week in August to end of second week in October 2022 in Zakho city, Kurdistan, Iraq. This period was characterized by variable weather parameters such as solar radiation, wind speed, atmospheric temperature, atmospheric pressure, dew point, and relative humidity. These variable weather conditions resulted in a wide range of variable daily yields and thermal efficiency values, ranging from 1,200–4,250 mL/d and 26%–45%, respectively. The analysis suggests that the average daily still thermal efficiency is linearly proportional to the incoming total daily solar radiation, with daily deviations from this linear average caused by other variable weather parameters.

Keywords: Effect of weather on solar still performance; Modeling of solar still performance; Single slope solar still; Thermal efficiency

1. Introduction

The shrinking global freshwater resources caused by multiple factors, such as climate change, industrial pollution, and the increasing world population, have prompted significant interest in technologies for seawater desalination to obtain drinkable water. Several large-scale and small-scale techniques are used for this purpose, and among the simplest, cheapest, and most popular ones is the solar still, which uses solar energy to evaporate and condense water. Consequently, the solar still has attracted considerable attention from experimental and theoretical researchers during the last three decades, seeking to improve its freshwater output and thermal efficiency through various modifications and techniques.

Several comprehensive reviews have summarized the developments and findings of solar still research from different angles. For example, Younis et al. [1] provided an overview of several types of solar stills, including single double slope and hemispherical ones, from experimental, theoretical, and computational perspectives. Essa et al. [2] presented a comprehensive review of papers investigating the effects of climatic, design, and operational parameters on solar still performance. Hasan [3] reviewed the impacts of design and operational modifications on the performance of both active and passive solar stills with different shapes. Ahmed et al. [4] surveyed various techniques used to enhance solar still performance, concluding that a typical efficiency of 30%–40% for a simple single-inclination solar still could be increased up to 60% with suitable

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modifications. Dsilva Winfred Rufuss et al. [5] reviewed the effects of using reflectors, heat storage materials, fins, collectors, and other enhancements on still performance. Abujazar et al. [6] pointed out that solar still productivity is highly affected by environmental parameters due to the unpredictability of weather conditions. Kalita et al. [7] reviewed the effects of different operating and geometric parameters on still performance and their thermodynamic optimization. Manchanda and Kumar [8] summarized the primary design and operational developments in single-inclination stills during the previous decade. Muftah et al. [9] analyzed many studies on factors affecting solar still performance, highlighting the significant influence of ambient conditions. Kaushal and Varun [10] provided a review of the design and properties of different types of solar stills. Yadav and Sudhakar [11] evaluated the economics considerations of different solar still designs emphasizing that various metrological parameter like solar radiation, wind speed, and ambient temperature and other design parameters greatly affect the performance of solar still.

In summary, the solar still is a promising technology for obtaining freshwater from seawater, but its performance depends on various factors that researchers have investigated and reported in multiple studies and reviews. Despite the numerous papers published on the structural, geometrical, and operational modifications of the solar still aimed at enhancing productivity and thermal efficiency, only a relatively smaller number of works have focused on the effects of weather conditions on solar stills' productivity and thermal efficiency. This is not entirely surprising since such studies require several weeks of solar still operation and monitoring. The most critical weather parameters that may affect solar still performance are solar radiation intensity, ambient temperature, relative humidity, wind speed, dew point temperature, and atmospheric pressure.

Studies have shown that as solar radiation (S) increases, freshwater output (M) from a particular solar still over a period of time also increases. Safwat Nafey et al. [12] proposed a linear model between the two variables using twelve monthly measurements of daily solar radiation and still yield. Khalifa and Hamood [13], on the other hand, fitted a quadratic relation between daily still yield and solar radiation using about 180 data points from eight references, including Cooper [14], Garg and Mann [15], Tanaka et al. [16], Ahmed [17], Zaki et al. [18]. Based on experimental measurements, Azooz and Younis [19] suggested a linear relationship between S and M. However, the question of whether the relation between S and M is linear or not remains open for further studies.

Xiao et al. [20] suggested that solar still productivity is expected to increase with increasing ambient temperature due to increased evaporation. Al-Hinai et al. [21] observed that an increase in ambient air temperature from 10°C to 12°C resulted in an 8.2% increase in productivity, while Koffi et al. [22] reported that a 5°C increase in ambient temperature can result in a doubling of still productivity.

Although increased wind speed is expected to result in increased heat transfer across the glass cover, causing cover cooling that assists condensation with a consequent increase in productivity, the experimental situation is not very clear. Experimental results by Panchal and Patel [23] showed an initial increase in productivity up to wind speeds of 3 m/s, followed by a slight decrease at higher speed values. Safwat Nafey et al. [12] used earlier suggestions by Malik et al. [24] that still productivity decreases with increasing wind speed to build a linear multi-correlation model.

Our search for literature related to solar still performance against relative humidity, dew point temperature and atmospheric pressure did not meet much success. A review article by Ithape et al. [25] suggested that an increase in relative humidity leads to an increase in solar still distillate output. However, no explicit published data relating still productivity or thermal efficiency to the atmospheric relative humidity could be cited.

The above literature scan indicates that there is a good case for carrying out detailed experimental measurements which produces sufficient data required for further assessment of the effects of different weather parameters on simple solar still performance on one hand, and attempting to empirically model the combined effects of these weather parameters on the other. This work is devoted to the experimental study of weather parameters on the performance of single slope solar still. The weather parameters involved are the daily solar radiation, ambient temperature (T_a), wind speed (W), relative humidity (H), dew point temperature (D_p) and atmospheric pressure (P). It may be worth pointing out that we were not able to find any published literature regarding the effects of the latter two weather parameters.

2. Experimental set-up

The experimental setup shown in Fig. 1 and used in this experiment consists of a 1 m^2 (1.33 × 0.75 m) rectangular solar still made from a 2 mm thick aluminum sheet. The still basin depth is 12.5 cm. The inclination angle of the 4 mm thick glass cover is 25°. The still is thermally insulated from all sides and the bottom with 5 cm thick plastic foam. The water level within the still basin is kept constant at 5 cm using a floating ball. The water condensed on the inner glass surface is collected via a horizontal channel into a plastic container. Feed water temperature, basin water temperature, inner and outer surfaces glass cover temperatures, still vapor temperature, and atmospheric temperature are recorded every 5 min using K-type (nickel-chromium/nickel-alumel) thermocouples with a sensitivity of 41 μV/°C each. The set of these thermocouples are connected to an Arduino electronic data acquisition system, which logs acquired data to the PC. The schematic diagram of the still is shown in Fig. 1a. The actual view of the still is shown in Fig. 1b. Weather parameters including temperatures, relative humidity and wind speed are recorded every 5 min using a Nexus Wireless Weather Station positioned beside the solar still. Furthermore, all hour-by-hour weather parameters including temperatures, wind speed, relative humidity, dew point and atmospheric pressure are obtained from Zakho Meteorological Station. The comparisons between the two sets of weather data showed that they are consistent within 1%. The minuet-by-minuet solar irradiation and total daily solar energy data were measured using cosine corrected solar radiation meter PCE-SPM 1

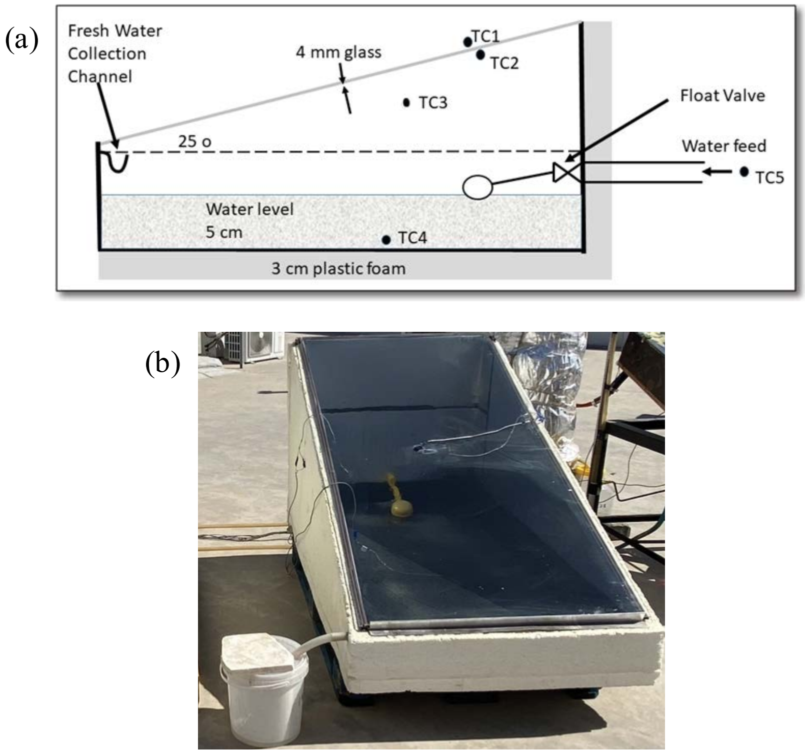

Fig. 1. Solar still (a) schematic diagram and (b) actual solar still.

Table 1
Experimental uncertainties

Quantity	Uncertain
Daily yield	1 mL
Daily solar radiation	0.01 kWh
Ambient temperature	1%
Wind speed	0.1 m/s
Relative humidity	0.2%
Atmospheric pressure	0.1 mb
Dew point	0.2°C

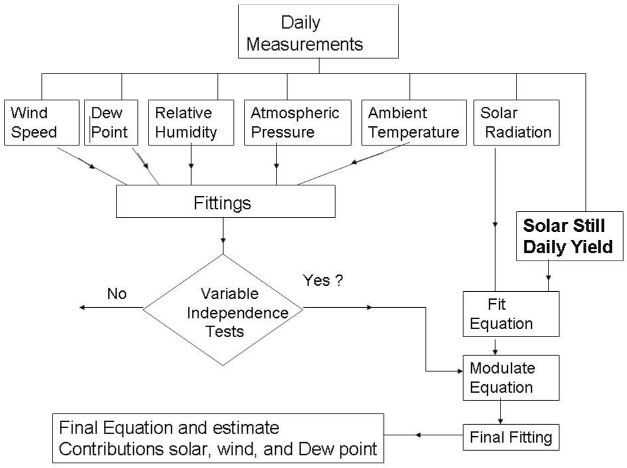

Fig. 2. Flow chart for data acquisition, analysis and modelling.

supplied by Tursdale Technical Services Ltd., UK [26]. The instrument has a computer logging system. Table 1 shows summary of all measurement's uncertainties involved in the experiment.

The distilled water is collected using a 10-L plastic container. In order to account for any water loss by evaporation from the container, the water loss from an identical container containing some water is measured over the same period. The daily collected distilled water quantities are measured using a digital weight-measuring device of 1 g sensitivity. The daily water quantity evaporated from the second container is added as a correction to the water quantity produced by the solar still.

Daily freshwater outputs over the period of seven weeks starting from the last week in August until the end of the second week in October were recorded together with their associated weather parameters. The flow chart of all steps involved in the data acquisition, analysis, and empirical modeling is shown in Fig. 2.

3. Results

3.1. Weather parameters

This work is done at the physics department at Zakho University research activities. The coordinates of the city of Zakho in Kurdistan – Iraq are 37.1505°N, 42.6727°E and 429 m above sea level. Its climate is described as being a Mediterranean, hot summer climate (Classification: Csa) [27] on Köppen–Geiger Climate Classification System [28].

Fig. 3 shows the distributions of daily weather parameter values (daily solar radiation, average daytime temperature, mean relative humidity, mean wind speed, mean dew point, and absolute atmospheric pressure for the period of the experiment.

3.2. Effect of solar radiation

Fig. 4a shows the relation between total daily solar radiation (S) and the daily accumulated freshwater production (M). Fig. 4b shows the relation between S and the solar still productivity (P) defined as the amount of fresh water produced per kilowatt of solar radiation.

$$P = \frac{M}{S} \tag{1}$$

Fig. 4c shows the relation between S and the still thermal efficiency (E). The thermal efficiency is defined as the output thermal energy of the evaporated water divided by the solar energy heat input.

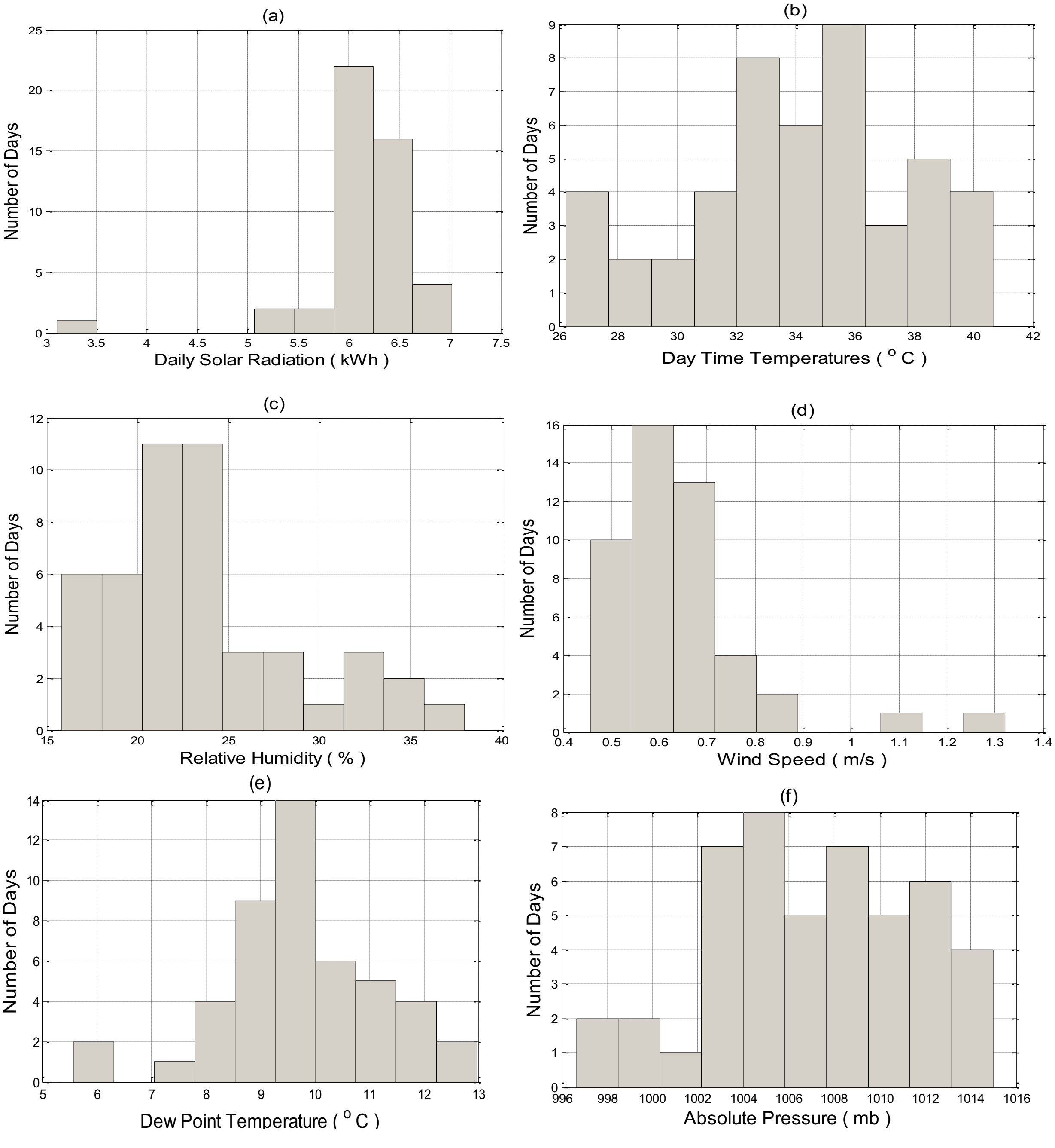

Fig. 3. Distributions of daily Zakho weather parameter values during the time of the experiment. (a) Solar radiation, (b) average daytime temperature, (c) daytime relative humidity, (d) mean wind speed, (e) dew point, and (f) atmospheric pressure.

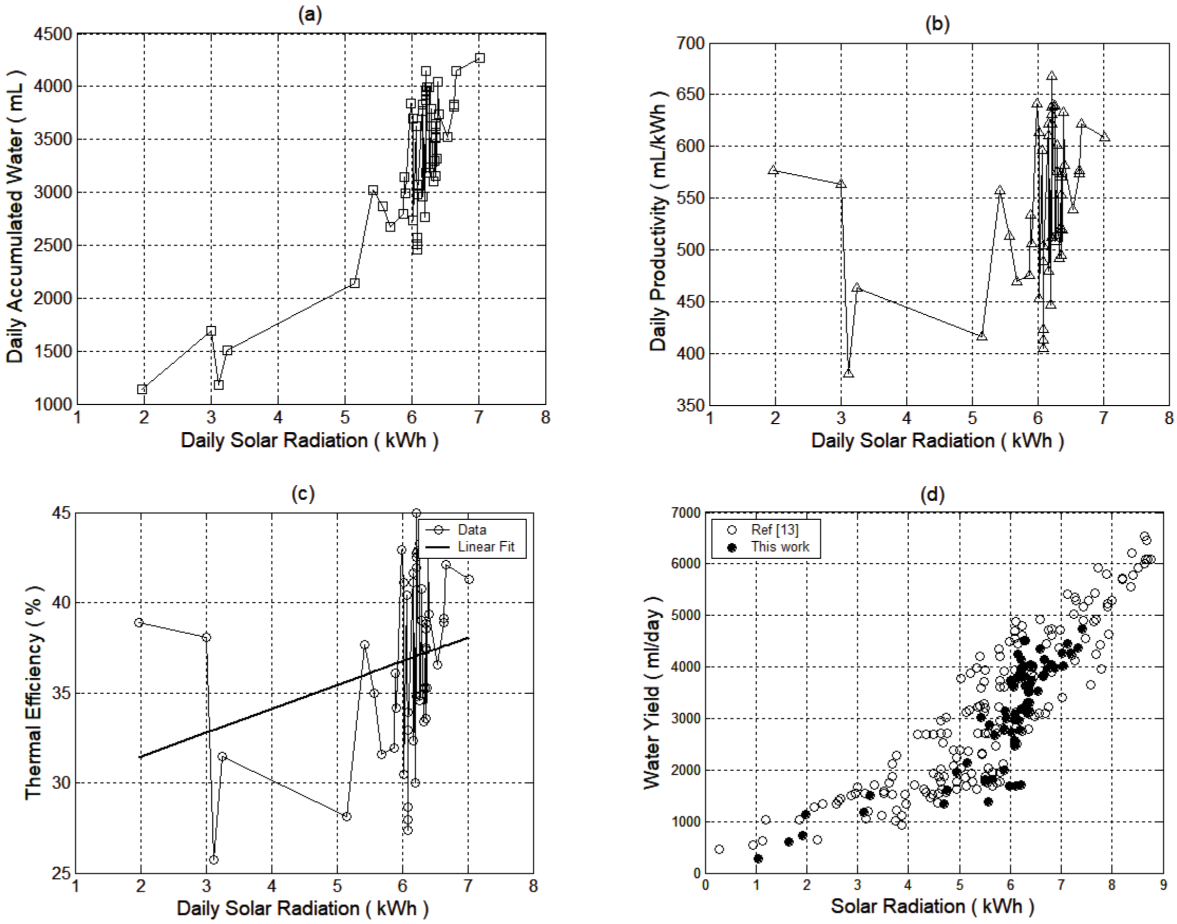

Fig. 4. Effect of total daily solar radiation on (a) accumulated water produced, (b) still water productivity, (c) still thermal efficiency, and (d) comparison of still daily yield with published data.

$$E = \frac{\text{Output Thermal Energy}}{\text{Input Solar Energy}} = \frac{M \times L}{S} \tag{2}$$

L is the latent heat of water vaporization at the initial temperature. The latent heat of water vaporization at a temperature (T_0) is given by the study of Tiwari and Tiwari [29]:

$$L = 2.4935 \times \left(1 - 9.4779T_0 + 0.13132T_0^2 - 4.7974 \times 10^{-3} T_o^3\right) \tag{3}$$

Online latent heats at different temperatures calculator is also available [30].

Fig. 4 suggests that although all three quantities show general increase with increasing solar radiation, there are also large fluctuations. In other words, there are significant differences in values for the corresponding close radiation values. For example, for the eight solar radiation values in the range of 6.086–6.21 kWh, the corresponding thermal efficiency assumed values between 27%–45%. This corresponds to the fact that the same solar still has produced quantities of freshwater ranging between 2,500–4,300 mL on different days having about equal solar radiation values. This should not be considered surprising, because such variations are reflections of the effects of other weather parameters on the productivity and efficiency of the solar still. This supports the case for more emphasizes on the study of the effects of other weather parameters on the still performance. Daily freshwater yield from this work compares well with corresponding data compiled in Fig. 3 by the study of Khalifa and Hamood [13]. The latter were retrieved using special image processing software and plotted together with data from this work in Fig. 4d.

The rest of this presentation will be concentrated on thermal efficiency rather than continuing with the discussion on distilled water produced or the productivity per kWh. This is because that although all three quantities are related, thermal efficiency is regarded as a better parameter, which describes the solar still performance because the effect of initial water temperature is included in the calculation. Thermal efficiency data of Fig. 4c are fitted with a linear relation of the form.

$$E = 4.43 \times S + 9.54\% \tag{4}$$

3.3. Effect of ambient temperature

Fig. 5 shows the effect of ambient temperature (T_a) on the still efficiency. It is clear from the figure that the efficiency is highly sensitive to ambient temperature. In spite of the fluctuations resulting from the effects of other weather parameters, the data can be fitted with a linear relation with 95% confidence level. The fitted equation is:

$$E = 1.1 \times T_a - 0.93\% \tag{5}$$

Eq. (5) is physically self-constant. It suggests that the still efficiency drops to zero at temperature at about 0.85°C, which is very close to the water freezing point. The equation also suggests that the efficiency reaches 100% at 92°C which is close to the water boiling point. Eq. (5) predicts that there will be about 1% additional increase in the percentage thermal efficiency for every one degree increase in ambient temperature. This is not in disagreement with predictions of numerical modeling proposed by Ithape et al. [25] which suggest increase of 3% in efficiency for every 5°C increase in ambient temperature.

3.4. Effect of relative humidity

Experimental data relating thermal efficiency and atmospheric daytime relative humidity (H) are shown in Fig. 6. Result clearly shows that the still thermal efficiency drops significantly with increasing air relative humidity. Attempts to fit the data with a linear equation resulted in an ill-valued Jacobean, which corresponds to low confidence level fit. An alternative negative exponential relation between E and H produced better confidence level fit of over 95%. The fitted relation is:

$$E = 46.58e^{-(H/19.6)} + 22.14\% \tag{6}$$

Eq. (6) is also physically self-consistent. It suggests that solar still efficiency is maximum under dry air conditions, and it approaches a limiting value of about 22% when the air is saturated with water vapor. Although there is not much literature experimental data on the effect of relative humidity on solar still productivity, the observed drop in thermal efficiency with increasing relative humidity is in disagreement with one of the conclusions made by the study of Abujazar et al. [6]. This conclusion, which states that productivity increases with increasing relative humidity, is based on results from two references. The first are experimental results reported on underground condensation measurements by Lindblom and Nordell [31]. The second are model calculations presented by the study of Tanaka et al. [16]. The latter concludes that relative humidity of 40% and temperature of 35°C, are optimum conditions for solar still yield. It is useful to remember here that the relative humidity plays two opposite roles in solar still operation. While increased humidity works to hinder evaporation form the still basin, it acts on the other hand to assist condensation on the glass cover. Our experimental results suggest that the first process is the dominating one.

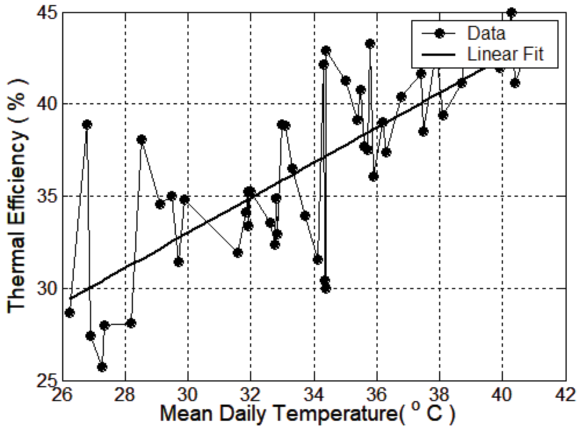

Fig. 5. Relation between solar still efficiency and ambient temperature.

3.5. Effect of wind speed

Thermal efficiency is plotted against wind speed (W) in Fig. 7. In spite of the large fluctuations, which again represent signatures of effects of other weather parameters, the figure shows a general weak decrease in efficiency with increasing wind speed. Although this decrease is inline with results of Malik et al. model [24] calculations presented in Fig. 5 [12]. Our and the associated linear fit to Eq. (7)

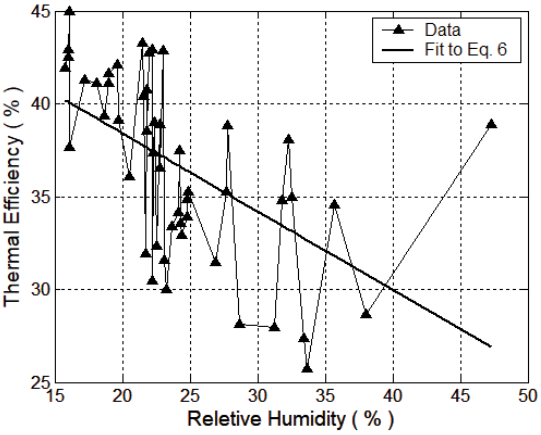

Fig. 6. Experimental results of solar still thermal efficiency against relative humidity.

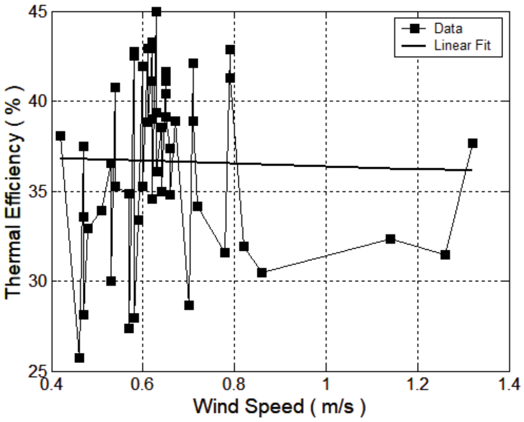

Fig. 7. Effect of wind speed on thermal efficiency.

show much faster decrease of yield, and consequently efficiency with increasing wind speed. These results are in disagreement with results of Ithape et al. [25] in Fig. 6, which shows increase in still yield with increasing wind speeds within the same range of wind speed values.

$$E = -0.73 \times W + 37\% \tag{7}$$

3.6. Effect of dew point

The relation between still thermal efficiency and dew point is shown in Fig. 8. In spite of the normal large data fluctuations, the data can be fitted to linear Eq. (8). No experimental, theoretical, or model predictions regarding the effect of dew point on still performance could be cited in literature.

$$E = 0.55DP + 31\% \tag{8}$$

3.7. Effect of atmospheric pressure

Fig. 9 shows the dependence of still thermal efficiency upon absolute atmospheric pressure. No literature data or predictions concerning solar still response to change in atmospheric pressure could be cited. The data here do not produce acceptable linear fit. Instead, a half-Gaussian type relation resulted in over 95% confidence level fit. The fitted equation is:

$$E = 42.1\exp\left\{-\left[\frac{\left(P-998\right)^2}{705}\right]\right\}\% \tag{9}$$

4. Modeling

In spite of the simplicity of solar still as far as its construction and operation are concerned, the quantitative heat and mass transfer analysis leading to the estimation of the still efficiency under different weather conditions is not a trivial task. Even under the assumption of ideal geometrical structure with no heat losses, the analysis of heat and mass transfer remains being governed by empirical relations and numerical parameters; Ayoobi and Ramezanizadeh [32], Kabeel et al. [33], Sri Hari Priya et al. [34] and Kwach et al. [35]. Under the circumstances, direct empirical parameterization of experimental solar still data may be another helpful approach to estimate still performance. Consequently, and based on the above experimental data and fitting results, we attempt to build an empirical model which predicts still thermal efficiency under different weather conditions. The model makes the following assumption:

- The driving parameter in solar still operation is the solar radiation (S). The linear dependence of still efficiency on daily-accumulated solar radiation described in Eq. (4) represents an average linear relation.
- Scattered daily deviations of experimental data points from the fitted linear relation represent signatures of effects of other five weather parameters.
- The other 5 weather parameters act to modulate the average linear solar energy dependence.
- All above dependences should be of the same mathematical nature obtained from above fittings.
- The partial effects of each of the weather parameters are to be obtained from fitting all experimental data to a model equation.

Consequently, one can put down a simple model equation which assumes linear solar energy dependence $f_0(S)$ modulated by the combined effects of other five weather parameters discussed above. However, and apart from the solar energy variable S, other model parameters candidates must be checked as being independent of each other. Not all the other five weather parameters studied above satisfy this condition. Some pairs involve strong correlations. Fig. 10 shows the correlation relations between all 5 weather parameters. It is clear from the figure that temperature, relative humidity and atmospheric pressure are strongly correlated to each other and only one of them needs to be included in the modeling. This mathematically means that including only one of them in the modeling will inherently take care of the effects of the other two. The temperature is chosen here for convenience. Dew point temperature and wind speed do not show significant correlation to any other weather parameter and thus they need to be included as independent parameter in the modeling. The modeling now needs to involve only four weather parameters as

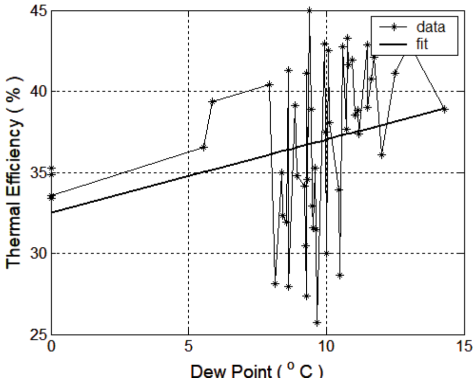

Fig. 8. Effect of dew point temperature on thermal efficiency.

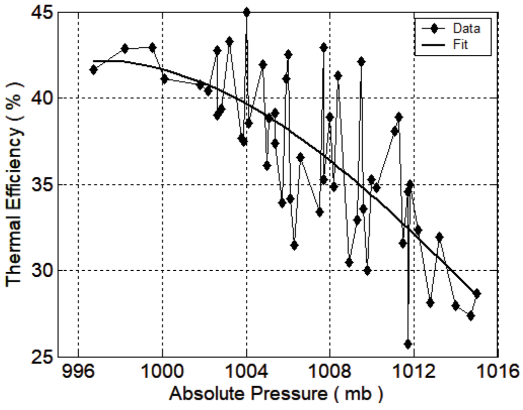

Fig. 9. Relation between atmospheric pressure and solar still efficiency.

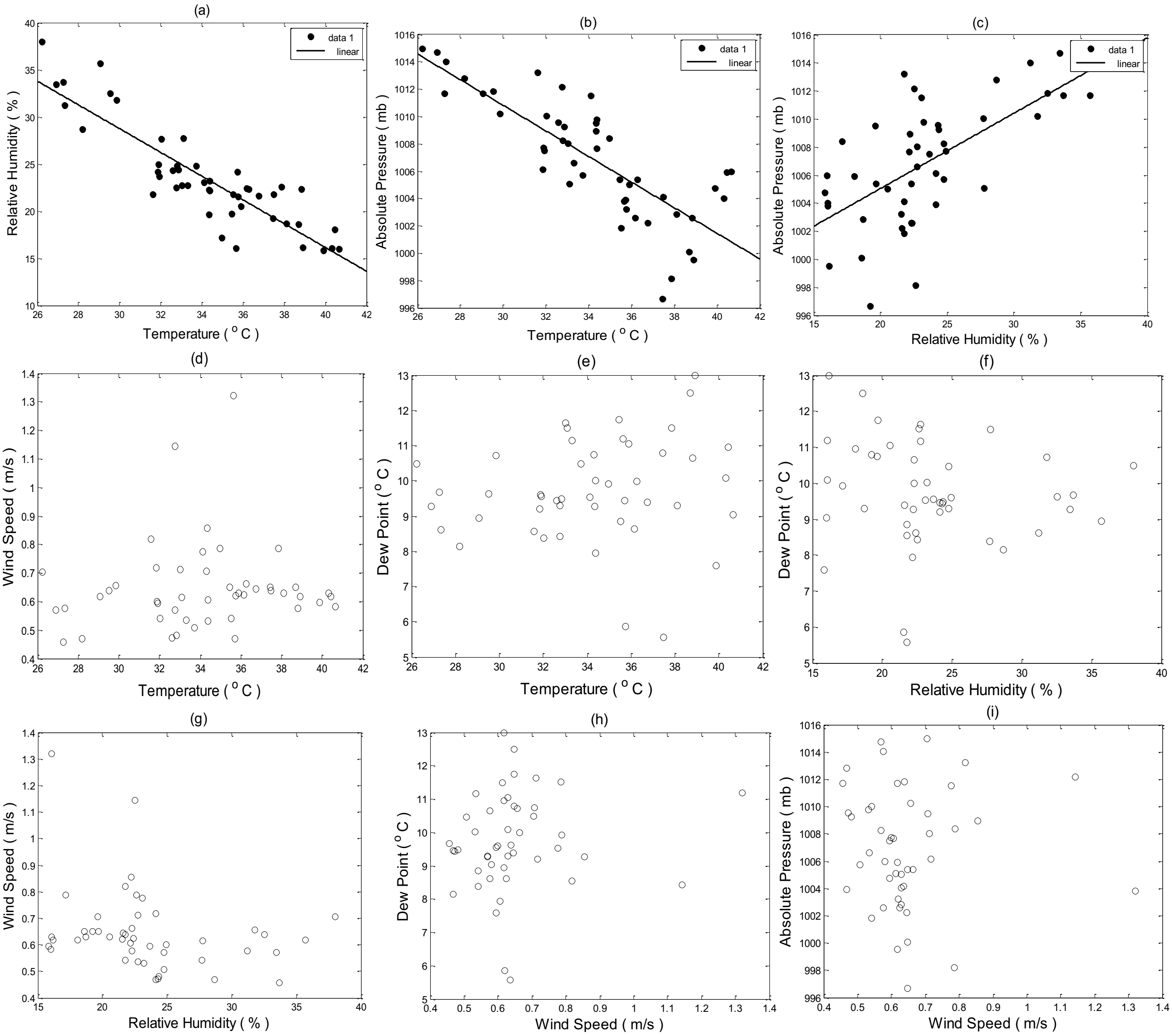

Fig. 10. Correlations between different weather parameters. Dependent parameters are in black circles. Independent parameters are white circle.

independent variables. These are the solar radiation, temperature, dew point temperature, and wind speed.

Individual fittings of still efficiency presented earlier showed that the efficiency is reasonably describable by linear Eqs. (4)–(8) to all four variables. The general forms of these linear relations are:

$$E = A_1 S + A_2 \tag{10}$$

$$E = B_1 T + B_2 \tag{11}$$

$$E = C_1 D_p + C_2 \tag{12}$$

$$E = D_1 W + D_2 \tag{13}$$

Based on the above arguments that the overall effects of all parameters can be represented by modulating solar radiation dependence in Eq. (10) by the linear superposition of Eqs. (11)–(13), we write:

$$E = A_1 S \times \left[\left(B_1 T + B_2 \right) + \left(C_1 D_p + C_2 \right) + \left(D_1 W + D_2 \right) \right] + A_2 \tag{14}$$

Simplifying and arranging terms gives:

$$E = S \times \left(a_1 T + a_2 D_p + a_3 W + a_4 \right) + a_5 \tag{15}$$

with $a_4 = \left(A_1 B_2 + A_1 C_2 + A_1 D_2 \right)$ and $a_5 = A_2$ (16)

The parameters a_1, …, a_5, are free fitting parameters to be determined by the program. The first three represent the partial effect of each of the three weather parameters on the solar still efficiency under a particular solar energy radiation condition.

The three free fitting parameters a_1, a_2, and a_3 are metrics of the partial effect of their corresponding weather parameters. The experimental data are fitted to Eq. (15) using a MATLAB software written for this purpose. The software uses least square fitting procedure to produce fits with over 95% confidence level. The inputs to the program are the four daily weather parameters and the corresponding solar still thermal efficiency calculated from the measured daily-accumulated freshwater output, and water feed temperature, using Eqs. (2) and (3). Fig. 11 shows the experimental data together with the fitted results.

The figure demonstrates that the model produces results which are in reasonable agreement with the experimental data. Calculations show that the average absolute differences between corresponding points are 5.4%. The distribution of these differences is presented in Fig. 12. The histogram shows that two thirds of the percentage differences are less than 6%. Only six out of forty-seven data points have differences higher than 10%. This suggests that model calculations are very much consistent with experimental data. The values of the three fitted metric parameters are listed in Table 2. Their values show that ambient temperature has the strongest effect on still efficiency. It contributes to about three quarters of the fluctuations from the linear solar radiation relation. Wind and dew point are collectively responsible for the remaining quarter.

5. Discussion

Eq. (14) represents the main result of the above modeling. It simply gives the values of the simple single inclination daily solar still efficiency as a function of daily solar radiation, ambient temperature, wind speed, and dew point. The accuracy of Eq. (14) predictions is about 5%. One important issue in this respect is the use of dew point temperature as one of the important weather parameters affecting solar still performance. No previous attempt to invoke this parameter in solar still modeling could be cited up to our knowledge. This means that the main weather parameters which need to be considered in any solar still modeling are the solar radiation, ambient temperature, wind speed and dew point temperature. Although other variable seems to affect solar still performance, their effects are physically and mathematically dependent on those of the above three, consequently, not to be included in the modeling. Experimental data and model calculations show that still efficiency can vary between 25% and 45% for the same solar radiation. This wide range of variation is the result of changing one or more of the above three weather parameters.

Ambient temperature seems to be a major player affecting still thermal efficiency at particular solar radiation intensity. Although many workers have presented experimental results demonstrating increases of still yield or thermal efficiency with increasing ambient temperature, most such measurements are for accumulative hour-by-hour outputs. In such measurements, effect of ambient temperature increases cannot be separated from solar radiation increase. A theoretical model proposed by Köppen Climate Classification [28] suggested that increase in the order of 3% in the performance of solar stills was made possible by an ambient temperature increase of 5°C. Muftah et al. [9], reported that an increase in ambient temperature

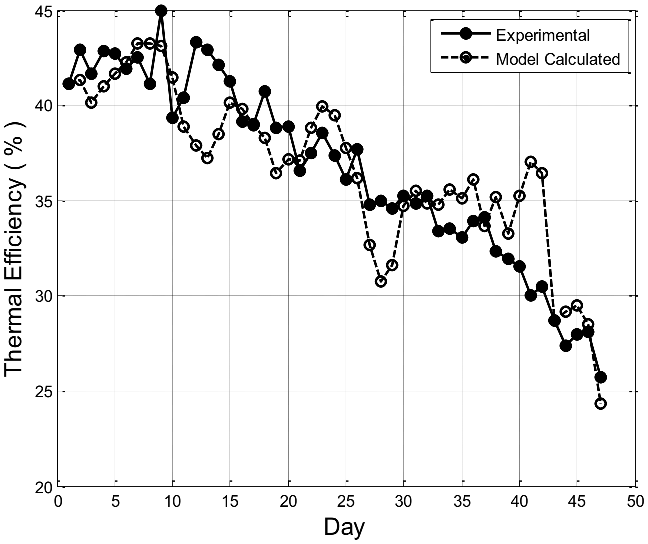

Fig. 11. Comparison between experimental and model predicted daily thermal efficiency.

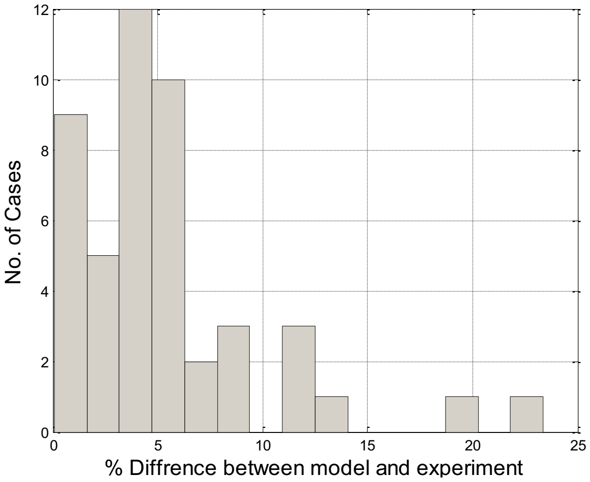

Fig. 12. Distribution of percentage differences between experimental data and Eq. (14) predictions.

Table 2
Partial percentage effect contributions of weather parameters to solar still thermal efficiency

Parameter	Weather variable	Fitted value	% Partial effect
a_1	Ambient temperature	0.1629	73.5%
a_2	Dew point temperature	0.0269	12.2%
a_3	Wind speed	0.0317	14.3%

of 10°C can increase distilled output by 8.2%. These results are in agreement with our model calculation of about 1% increase in efficiency per 1°C temperature increase.

Wind speed seems to have a significant effect on solar still efficiency. The model suggests that there is about 0.7% decrease in percentage thermal efficiency per 1 m/s increase in wind speed. Approximate results inferred from Tiwari and Tiwari [29] (Fig. 6), suggest a decrease in still productivity of about 0.3% per 1 m/s increase in wind speed. This is of the same order of magnitude of this model prediction.

Our attempts to cite literature related to the effect of dew point temperature of solar still performance did not meet much success. However, it is clear that changes in dew point temperatures can affect solar still efficiency to some extent. Model estimations give about 0.2% increase in thermal efficiency per 1°C increase in dew point.

6. Conclusions

The empirical model equation developed in this study offers a reasonable estimation of the daily thermal efficiency of a single slope solar still based on four key weather parameters. Beside the daily solar radiation, the other three input weather parameters are the daily solar radiation, the mean daytime temperature, the mean wind speed, and the daytime dew point. Correlation analysis reveals that all other weather parameters are dependent on these three variables. Notably, this study introduces the dew point temperature as a factor in solar still performance analysis for the first time.

The model indicates that, for a given solar radiation value, there can be significant fluctuations of up to 80% in thermal efficiency caused by variations in temperature, wind speed, and dew point. Specifically, ambient temperature accounts for approximately 73.5% of these changes, while wind speed and dew point temperature contribute approximately 14.3% and 12.2%, respectively. Hence, it is crucial to accurately report the daily weather parameters in any study pertaining to modifications in evaporative solar stills.

Two key points need to be emphasized: firstly, the necessity of conducting experimental tests over multiple days under diverse weather conditions, and secondly, the essential requirement to compare the performance of any modified solar still system with an identical unmodified system operating under the same weather conditions.

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