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Indoor tests on the effect of wind speed on still performance

Abdul Jabbar N. Khalifa, Marwa AW. Ali

Al-Nahrain University, College of Engineering, Mechanical Engineering Department, Jadiriya, P.O. Box 64040, Baghdad, Iraq.

Abstract

Wind speed is an important parameter that affects the productivity and efficiency of solar stills. The literature shows conflicting opinions about the effect of wind speed on the total yield of fresh water from solar stills. One reason behind such discrepancy could be attributed to the uncontrolled effect of some of the meteorological parameters. This study reports an investigation on the effect of wind speed on the performance of basin type stills carried out indoor using a fan to generate airflow analogous to the outdoor wind and heaters to provide uniform heat flux to the basin. The tests were conducted for four different wind speeds of 1.14, 2.06, 2.92 and 4.01 m/s in addition to tests with stationary air. It was found that increasing wind speed will definitely increase the yield of solar stills and high wind speeds may give less improvement in productivity than moderate wind speeds.

Keywords: Solar still; Wind speed; Indoor test; Productivity; Heat flux.

1. Introduction

The performance of solar stills is affected by three different sets of parameters namely, design parameters (such as glass inclination and basin water depth), operational parameters (such as salinity of water, feed water preheating) and climatic parameters (such as wind velocity and solar radiation intensity). In contrast to the first two groups, the latter cannot be controlled as they are related to the conditions of the weather. However, some of these variables can be controlled to some extent if indoor tests are used. Hence, the performance of solar stills can be evaluated by using heaters beneath the still to simulate the energy from the sun and to provide the necessary heat for evaporation. It is possible to control the level of the input power by regulating the input voltage to the heaters and/or the number of heating elements used. Fan(s) may also be used to create a condition analogous to the outdoor wind on the body and condensing surface(s) of the still. Such measures allow some control on the input power and wind speed and thus should reduce the effect of outdoor conditions on the accuracy of the experimental results.

Wind speed is an important parameter that affects the productivity and efficiency of solar stills. The magnitude and trend of wind effect on several configurations of solar stills have been investigated in the literature. Table 1 summarizes the majority of the experimental and theoretical studies on this issue. It can be noticed from the table that most of the studies on wind effect is theoretical. One would expect that the results from these theoretical studies agree as they are all based on the same fundamental relations of heat and mass transfer. However, discrepancy among the results of these studies is evident even for the similar configurations of stills. The verdict about the effect of increasing wind speed on productivity varies among the theoretical investigations from negative [1-5] by up to 13% [5], insignificant [6, 7], to positive [8-13] by up to 50% [13]. Moreover, some investigations propose a certain optimum value of wind speed at which the maximum yield is obtained [14-17].

Table 1. Summary of studies on how wind speed affects solar still performance

Author(s)	Configuration	Conclusion about the effect of wind speed
Outdoor/ Theoretical Studies		
Elsherbiny and Fath [1]	Single slope still	Increasing the wind speed cause a small reduction in still productivity
Nafey et al. [5]	Single slope still	Increasing the wind speed from 1 to 9 m/s decreases the productivity by 13%
Fath and Hosny [6]	Single slope still with enhanced evaporation and additional condenser	Wind speed from 0-5 m/s has insignificant influence on the productivity
Fath et al. [7]	Naturally circulated humidifying/dehumidifying solar still	Increasing wind speed from 0-5 m/s has little effect on the productivity
Zurigat and Abu-Arabi [13]	Regenerative single slop still	Increasing the wind speed from 0-10 m/s can increase the productivity by more than 50%
Mamlook and Badran [8]	Asymmetric greenhouse type with mirrors on its inside walls	Increasing the wind speed from 3.1-5 m/s increase the productivity by 15%
Elsafty et al. [2]	Still that uses parabolic reflector-tube absorber	increase the wind speed from 0-5 m/s, decreases the productivity marginally
Madhlopa and Johnstone [3]	Single slope still with evaporator and condenser chambers	Wind speed (range 2-6 m/s) reduce the productivity marginally
Tiwari et al. [9]	Passive and active stills integrated with a flat plate collector	Productivity increase continuously with increasing wind speed (range 0-5 m/s)
El-Sebaii [14, 15, 16]	Basin type stills	There is a critical mass/depth of basin water (45 kg/4.5 cm) beyond which productivity increases as wind velocity increases up to a typical velocity of 10 and 8 m/s on typical summer and winter days, respectively.
Outdoor/ Combined Theoretical and Experimental Studies		
Morse and Read [4]	Double slope solar still	The influence of wind on productivity is unimportant, (range 2.24-8.94 m/s). The difference in productivity is only 3 %
Toure and Meukam, [10]	Single basin solar still	The wind speed has little effect on productivity. Increasing wind speed from 0-9 m/s increases the production by 10%
Abdenacer and Nafila [11]	Green-house effect solar still	Productivity increases with wind velocity
Dimri et al. [12]	Active solar still coupled to two flat plate collectors	As wind speed increases from 1-5 m/s, the productivity increases
Kumar and Tiwari [17]	Shallow basin solar still	The exergy efficiencies increase rapidly for wind speed up to 2 m/s and decreases further
Outdoor/ Experimental Studies		
Farid and Hamad [18]	Single basin solar still	There is a significant decrease in efficiency with the increase of wind velocity
Badran [20]	Single slope solar still	Productivity increases by 35% with increasing wind speed from 2.7-5 m/s
Younis [19]	Single slope solar still	Productivity decreases slightly as wind speed increases (range 0-8 m/s)

Indoor Studies		
Maalej [21]	single slope basin still, large size fan High and medium intensity bulb projectors are used to give three intensity levels of 1009.4, 709.77 and 346.99 W/m²	The increase in wind velocity from 0-1.6 m/s yields a reduction of 2% in the still performance (range 0-3.35 m/s)

Experimental studies on the effect of wind speed on still performance are scarce in the literature. Again, discrepancy among these studies is noticed. While Farid & Hamad [18] and Younis et al. [19] found a negative effect of wind speed on productivity, Badran [20] reported a positive effect by up to 35%.

As far as indoor investigations on the effect of wind speed on stills is concerned, Maalej [21] carried out an experimental and theoretical study by simulating the external breeze on his still using a large size fan to generate a uniformly distributed air flow analogous to wind outdoor. A reduction of only 2% in the still performance was reported when the wind velocity is increased from zero to 1.6 m/s.

The literature survey shows conflicting opinions about the effect of wind speed on the total yield of fresh water from solar stills. This parameter is sensitive and must be studied to reach a conclusion about its effect. One reason behind the discrepancy among the conclusions of the different studies may be attributed to the uncontrolled effect of some of the meteorological parameters. Accordingly, the aim of the present research work is to investigate the effect of wind speed on the performance of the basin type still by thorough tests inside the laboratory during which the power input and wind speed are simulated by a suitable heating system and a variable-speed fan respectively, and thus minimizing the effect of some of the factors that affect the accuracy of the experimental results.

2. Experimental work

A single sloped basin type still is constructed from a galvanized steel sheet 0.8 mm thick to form 0.7 by 0.7 m basin. A glass cover 4 mm thick is placed on the top of the basin at a slope equal to the latitude angle of the location of 33° from horizontal [22] to serve as a condensation surface. Silicon rubber sealant is applied on the glass cover to insure tightness of the still. The bottom and sides of the still is insulated with a sheet of glass wool 10 mm thick (thermal conductivity of 0.04 W/m °C) to increase heat retention. The whole construction is contained in a rigid plywood structure. A schematic of the experimental still showing the main components and locations of the temperature measurements is given in Figure 1.

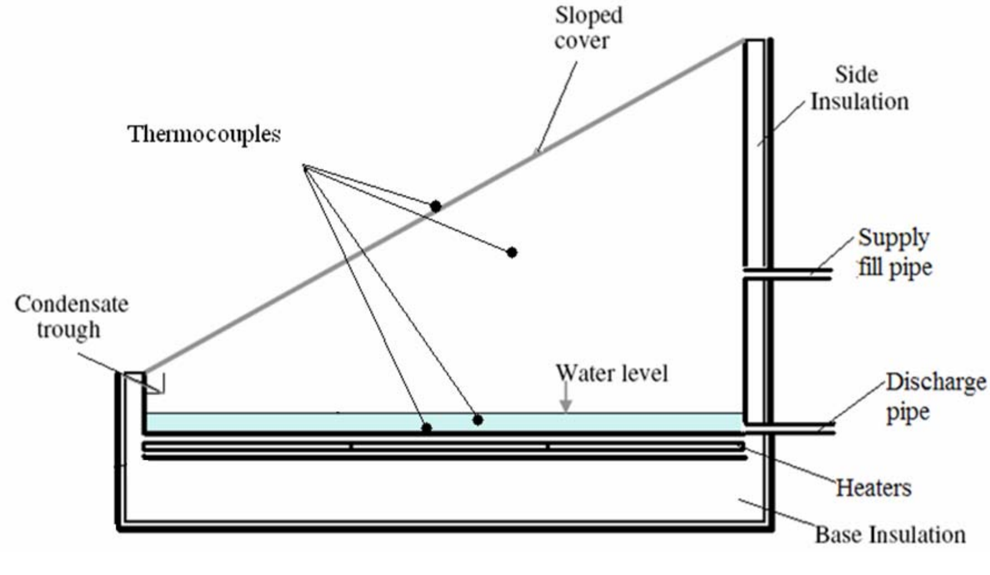

Figure 1. A schematic of the experimental still showing the main component and locations of temperature measurements

The heat input to the still from solar radiation in outdoor condition is simulated by a set of three electric heaters placed beneath the basin as shown in Figure 2. These heaters, which measures 66 by 21.5 cm each, are connected in series to supply a uniform heat flux to the basin area of the still. Each heater is manufactured by winding a wire that has a resistance of 2.5 Ω/m on a 0.4 mm thick sheet of mica which is then sandwiched between two similar sheets of mica. The whole construction is finally contained in a 1-mm-thick plate envelope of galvanized iron to prevent deformation of the mica sheets as they get heated. A variac (input 380 V, output 0-450 V, 50-60 Hz) is used to regulate the input voltage to the heaters and thereby the input power. The three heaters that are connected in series supply a maximum total power of 1000 W. The input voltage and current are constantly monitored to insure a stable power input to the heaters at the desired setting.

Figure 2. Three separate heaters connected in series at the base of the still

A graduated flask is used to collect the distilled water at half-hourly intervals for continuous five hours. All test are carried out during the same hours each day from 8:30 am to 1:30 pm to insure that the tests are carried out at an almost the same surrounding temperature in the laboratory. Obviously, apart from this point, local time does not mean much in indoor tests. The surrounding temperature during the tests were at a minimum of 15 °C and a maximum of 18 °C with an average value of around 16.6 °C.

Calibrated K- type thermocouples are embedded at various locations in the still (Figure 1) to measure the temperatures of the exterior surface of the glass cover, the vapor enclosed inside the still, the brine and the basin plate, in addition to the surrounding temperature. A12-channel temperature recorder data logger (Model BTM-4208SD) with a resolution of 0.1 °C and a sampling rate that can be varied between one second to one hour is used to record these measurements.

To simulate the wind speed in the indoor tests, a 280 W fan is situated in front of the still to create a condition analogous to the outdoor wind. The speed of the fan is controlled by varying the input voltage to the fan motor using an additional variac. Four different wind speeds are created, namely 1.14, 2.06, 2.92, 4.01 m/s. Tests at stationary air are also carried out. The speed of the wind is measured by placing a digital anemometer at a right angle to the sloped cover of the still. During these tests, the water depth in the still basin is kept at 4 cm and the output power of the heaters is set at 459 W (equivalent to 937 W/m²).

3. Basic heat and mass transfer relations

The operation of a solar still is governed mainly by convection and radiation. A very small amount of energy is also lost to the ground (or atmosphere) by conduction through the base. Within the still, convective heat transfer occurs simultaneously with evaporative mass transfer while radiative heat transfer occurs in the inside and outside regions along with other modes.

Dunkle [23] presented the following relations that account for the heat transfer across the bulk of the humid air inside the still by free convection, which is then released at the glass cover,

$$q_{cb} = 0.884\left[(T_b - T_g) + \frac{(P_b - P_g)(T_b + 273)}{268.9 \times 10^3 - P_b}\right]^{1/3} (T_b - T_g) \tag{1}$$

Or,

$$q_{cb} = h_{cb}\,(T_b - T_g) \tag{2}$$

where q_{cb} is the heat transfer by convection between the brine surface and the glass cover (W/m²), h_{cb} the convective heat transfer coefficient between the brine surface and the glass cover (W/m² K) and $T_b \,\&\, T_g$ the temperatures of the brine and glass respectively. The partial pressures P_b and P_g of the saturated vapor at the brine and glass cover temperatures (N/m²) respectively are calculated from,

$$P_b = exp\left[25.317 - \frac{5144}{(T_b + 273)}\right] \tag{3}$$

$$P_g = exp\left[25.317 - \frac{5144}{(T_g + 273)}\right] \tag{4}$$

The heat transfer by evaporation (q_{eb}) from the brine surface to the glass cover (W/m²) is,

$$q_{eb} = 16.273 \times 10^{-3}\, q_{cb}\, \frac{P_b - P_g}{T_b - T_g} \tag{5}$$

While the mass transfer rate is,

$$m_e = \frac{q_{eb}}{L} \tag{6}$$

where L is the latent heat of vaporization of brine (kJ/kg)
The water surface and the glass cover may be considered as infinite parallel planes in stills with small cover slopes and large dimensions, hence,

$$q_{rb} = \frac{\sigma\,(T_b^4 - T_g^4)}{[\epsilon_b^{-1} + \epsilon_g^{-1} - 1]} \tag{7}$$

where σ is the Stefan–Boltzmann constant and $\epsilon_b \,\&\, \epsilon_g$ are the emissivities of brine (=0.96) and glass (=0.88) respectively.
Absolute values of the total energy transfer rate are obtained by the addition of equations 2, 5 and 7.
Due to the small thickness of the glass cover, the temperature in the glass may be assumed uniform. The external radiation losses from the glass cover at T_g (K) to the surrounding surfaces at T_a (K) (T_{sky} in the outdoor tests) is expressed as,

$$q_{ra} = \epsilon_g\, \sigma\, [T_g{}^4 - T_a{}^4] \tag{8}$$

And the convection heat loss to the surrounding is given as,

$$q_{ca} = h_{ca}\,(T_g - T_a) \tag{9}$$

Hence,

$$q_a = q_{ra} + q_{ca} \tag{10}$$

The external convection coefficient h_{ca} is a function of air velocity V,

$$h_{ca} = 5.7 + 3.8V \tag{11}$$

The instantaneous thermal efficiency of still is the ratio of the thermal energy utilized to get a certain amount of distilled water (q_{eb}) to the input wattage per unit basin area at a given time interval $[W(t)]$, both being in W/m²,

$$\eta_i = \frac{q_{eb}}{W(t)} \tag{12}$$

4. Results and discussion

The time variation of the half-hourly accumulated yield of the still for different wind speeds during the test hours is shown in Figure 3. It can be seen that the yield increases steadily with time, which is obvious due to the heat input to the still. The still with no wind exhibits the lowest yield. An appreciable increase of 44.7% in yield during the test period is noticed when a wind speed of 1.14 m/s is applied. Increasing the wind speed further to 2.06, 2.92 and 4.01 m/s will cause further, but modest, increase of 9.1% and 11.6% and 5.5% respectively from the 1.14 m/s wind level. Figure 4 shows the variation of the yield per square meter of basin area against the wind speed. It can be seen here that the best result is obtained with a wind speed of 2.92 m/s that caused an increase of 61.6% in the yield in comparison to the no wind case. However, this improvement is not significantly larger than those of the other wind speeds tested as shown earlier. One may conclude that wind speed will definitely increase the yield of solar stills; however, increasing the wind speed to higher levels will not increase the yield much further. In the contrary, high wind speeds may reduce the improvement by a certain amount as with the case of the 4.01 m/s in this study.

To explore the reasons behind the productivity variation with wind speed, we look first at the effect of wind speed on some of the system temperatures. Figure 5 shows the time variation of brine and glass temperatures for different wind speeds. It can be seen that the glass temperature is noticeably reduced when a wind speed of 1.14 m/s is applied due to the increase in heat loss from the glass cover to the surrounding air. Further increase in wind speed will cause further, but modest, reduction in the glass temperature. A comparable behavior in brine temperature with wind speed can be noticed in the figure. However, the brine temperature is less sensitive to wind speed variation due to the higher heat capacity of the brine bulk compared to that of the glass cover and the direct contact of the latter with the moving air.

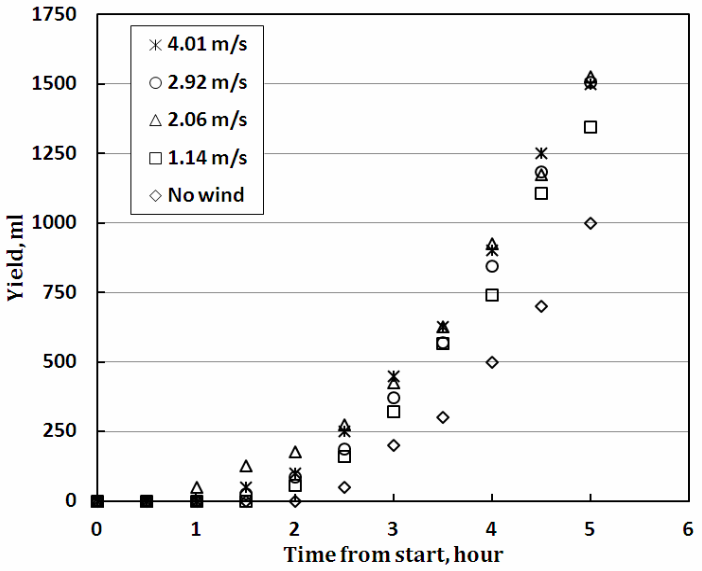

Figure 3. Variation of the half-hourly yield of the indoor still with time for different wind speeds

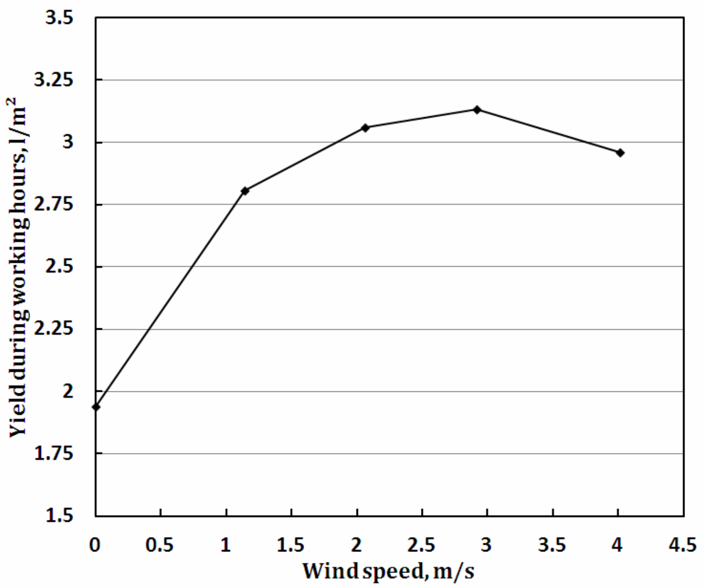

Figure 4. Variation of productivity during working hours with wind speed

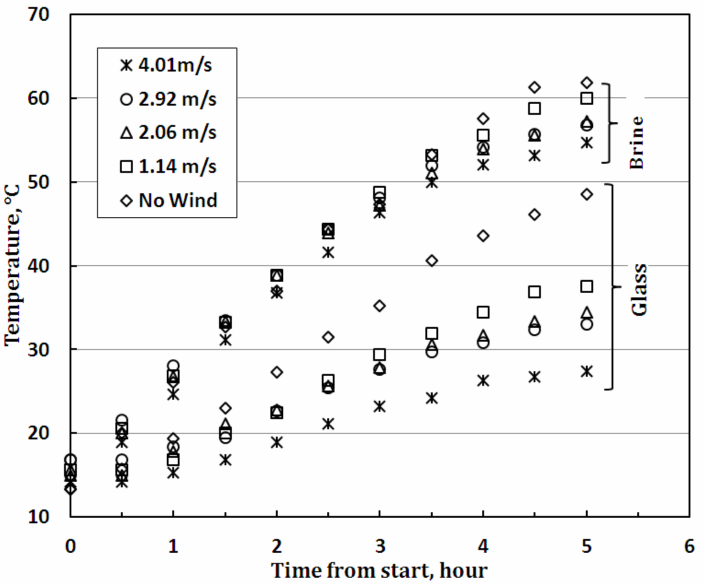

Figure 5. Variation of brine and glass temperatures with time for different wind speeds

The time variation of the brine-glass temperature difference, which is the driving potential of all heat fluxes inside the still, is plotted in Figure 6 for various wind speeds. Obviously, this difference is expected to vary in a similar manner to those of brine and glass temperatures. Consequently, applying 1.14 m/s wind speed increased the brine-glass temperature difference remarkably but further increase in wind speed will only cause modest additional increase in this difference.

It was shown in equations 1 to 5 that the brine-glass temperature difference is the driving potential of heat transfer by convection, radiation and evaporation inside the still. The productivity of the still is strongly related to the heat transport by evaporation. Figure 7 shows the time variation of this heat flux (W/m²) for the various wind speeds tested. Modest wind speed will cause the evaporative heat flux to increase remarkably due to the increase in the brine-glass temperatures as shown earlier; again, further increase will cause only slight increase in the evaporative flux. As the experimental results for the various wind speeds in Figure 7 is too close, the total energy transported by evaporation during the working period (area under each curve in W.h/m²) is calculated and plotted in Figure 8 against the wind speed. The trend of productivity variation with wind speed shown in Figure 4 and that of energy flux in Figure 8 is evident.

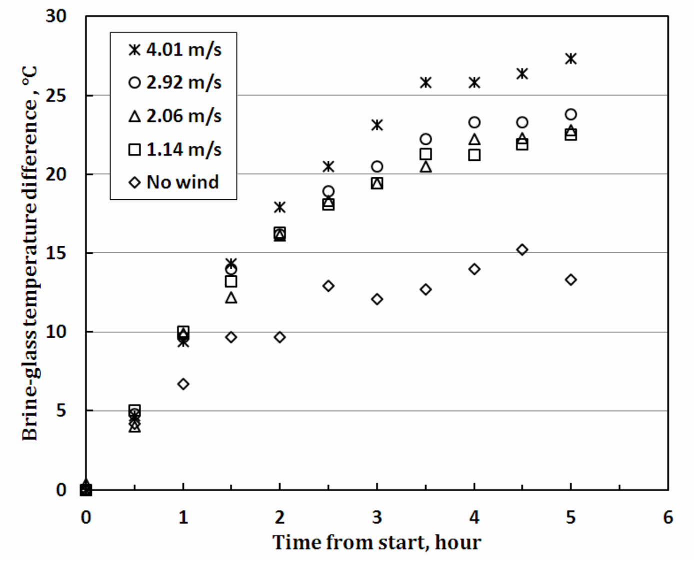

Figure 6. Variation of brine-glass temperature difference with time for different wind speeds

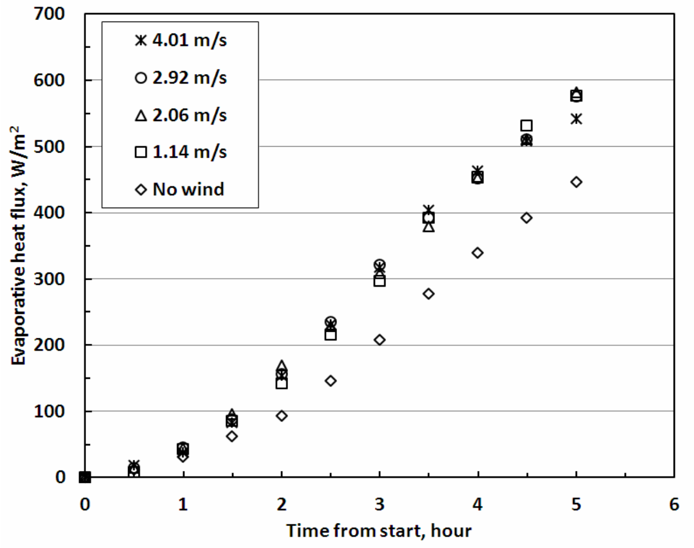

Figure 7. Variation of evaporative heat flux inside the still with time for different wind speeds

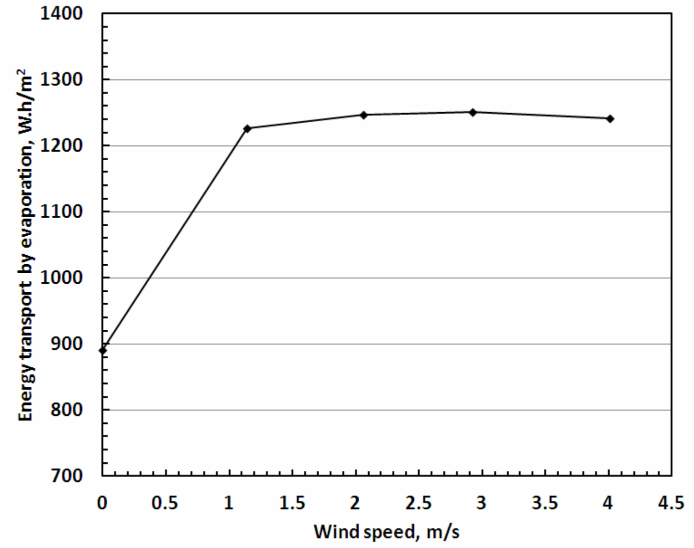

Figure 8. Variation of total energy transported by evaporation with wind speed

5. Conclusions

Indoor tests were conducted to investigate the effect of wind speed on the performance of basin type stills. This effect is examined by using a fan to generate airflow analogous to the outdoor wind, and heaters that provide uniform heat flux to the basin. The tests were conducted for four different wind speeds of 1.14, 2.06, 2.92 and 4.01 m/s in addition to tests with stationary air, all with an input power of 459 W and 4 cm brine depth. It can be concluded that increasing wind speed will definitely increase the yield of solar stills. However further increase in wind speed will not increase the yield much further. In the contrary, high wind speeds may give less improvement in productivity than moderate wind speed; in this study, this critical value was found to be around 4 m/s. The increase in productivity was found to cause an increase in the heat transport by evaporation inside the still due to the increase in the brine-glass temperature difference.

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Abdul Jabbar N. Khalifa holds a PhD in Mechanical Engineering from Cardiff University (UK) in 1989 in the field of heat transfer. His main research interests include Heat Transfer, Renewable Energy, Desalination and Nanofluids. He has published more than 40 papers in peer-reviewed journals. He is also a reviewer for several peer reviewed journals. Currently Dr. Khalifa is an assistant professor in the Mechanical Engineering Department in Al-Nahrain University, Iraq.
Email address: ajkhalifa2000@gmail.com

Marwah AW. Ali Ms. Ali holds an MSc degree in Mechanical Engineering from Nahrain University, College of Engineering (Iraq) in 2012. Her main research interest is Renewable Energy and Thermofluid Sciences.
Email address: bilalrabah11@yahoo.com