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Numerical Investigation of the Effect of Wind Speed on Performance of Single-Slope Solar Still

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Single-slope solar still; performance; wind speed; vapour concentration; numerical analysis.

ABSTRACT

Pure water is an essential element for human life and other living organisms, as well as for industrial and construction processes. Many technologies have been used to produce drinking water. Most of them depend on fossil fuels as an energy source, but due to the continuous rise in fuel prices, the phenomenon of global warming, the weakness of infrastructure in many developing countries, and other factors, renewable energy has become the ideal solution to be an energy source.

In this study, the effect of air velocity on the internal vapor content and its relationship with the performance of a conventional single-slope solar still was investigated numerically by Comsol Multiphsics 5.3 software. It was found that the productivity of a solar still is directly affected by the air velocity directed towards the glass cover. The forced directed air works to cool the glass cover, which leads to an increase in the temperature difference between the turbid water layer and the transparent cover layer, which enhances the condensation rates of the vapor mass at the glass cover, thus increasing the yield rate. The results showed that the total productivity of fresh water increased by about 4.7%, 10.3%, and 16% when the air velocity on the glass cover was (1.5, 3, and 4.5) m/s, respectively, compared to 0.5 m/s.

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دراسة عددية لتأثير سرعة الرياح على أداء المقطر الشمسي أحادي المنحدر

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ملخص: الماء النقي عنصر أساسي لحياة الإنسان والكائنات الحية الأخرى، وكذلك للعمليات الصناعية والبناء. وقد استخدمت العديد من التقنيات لإنتاج مياه الشرب. يعتمد معظمها على الوقود الأحفوري كمصدر للطاقة، ولكن بسبب الارتفاع المستمر في أسعار الوقود، وظاهرة الاحتباس الحراري، وضعف البنية التحتية في العديد من البلدان النامية، وعوامل أخرى، جعلت من الطاقة المتجددة الحل الأمثل لتكون مصدرًا للطاقة. في هذه الدراسة، تم التحقيق في تأثير سرعة الهواء على محتوى البخار الداخلي وعلاقته بأداء جهاز التقطير الشمسي التقليدي أحادي المنحدر رقميًا بواسطة برنامج Comsol Multiphsics 5.3 . وقد وجد أن إنتاجية جهاز التقطير الشمسي تتأثر بشكل مباشر بسرعة الهواء الموجه نحو الغطاء الزجاجي. يعمل الهواء الموجه القسري على تبريد الغطاء الزجاجي، مما يؤدي إلى زيادة الفرق في درجة الحرارة بين طبقة الماء العكر وطبقة الغطاء الشفاف، مما يعزز معدلات تكاثف كتلة البخار عند الغطاء الزجاجي، وبالتالي زيادة معدل العائد. وأظهرت النتائج أن الإنتاجية الكلية للمياه العذبة زادت بنحو 10.3%، 4.7%، و 16% عندما كانت سرعة الهواء على الغطاء الزجاجي (3، 1.5، و4.5) م/ث على التوالي مقارنة بـ 0.5 م/ث.

الكلمات المفتاحية – المقطر الشمسي احادي الميل, الاداء, سرعة الرياح, تركيز كتلة البخار, التحليل العددي.

1. INTRODUCTION

Due to various environmental, health, economic and global security factors, many researchers have presented various studies on the use of free solar energy applications of various types [1-5]. The remarkable change in climate and the persistent need for fresh water in different regions of the world have led to the use of different methods of freshwater production by many researchers [6]. Desalination of salt water requires a large amount of electrical energy. In general, the electrical energy consumed to desalinate 1 m3 of seawater can be estimated at about 0.86 kWh [7]. The use of available solar energy should be considered an effective solution in light of the many environmental, health, and economic challenges facing humanity [8-11]. Many studies showed that renewable energy can provide almost 100% of the total local energy [8,9]. The most commonly used method is to use the available solar energy to desalinate sea water because of its low cost and ease of use when compared to other methods. However, the use of solar energy for the purpose of distillation challenges many constraints, the most important of which is low productivity [12]. Previous studies have shown that the use of solar distillation can be useful when water demand is low and the weather conditions are suitable [13]. The traditional single-slope solar still model is most commonly used in solar distillation processes. The operation of the model is limited by evaporation and condensation. Studies have shown that productivity does not exceed 2-3 L/m^2.day [14]. El-Sebaii [15]presented a numerical study to show the effect of wind speed on the productivity of the model, and it was found that increasing wind speed caused an increase in the amount of daily productivity. Tarawneh [16] studied the effect of cooling the tilted glass lid of the still on productivity. The still basin contains turbid water at different depths, and the results showed that productivity increased by 17–23%. Hasnain Ghani Hameed et al.[17] numerically studied the effect of using fins of various geometric shapes on the productivity of conventional solar stills. The experimental results showed that welding the conical fins to the absorption part can enhance the yield by the largest amount of freesh water, which can reach 4.13 kg/m^2 with an enhancement ratio of 38.2%. Hassanain et al. [18]practical evaluated the effect of cooling the glass cover of the model using different air speeds, and they found that increasing air to 4 m/s caused a boost in output of about 22.8%. Through most of the studies presented on solar stills of various types, we notice the paucity of studies that adopted and discussed the subject of the speed of air passing over the glass cover and the extent of its effect on the concentration of steam inside the closed area of the proposed still and its relationship to the total productivity of the yield. The main objective of this work is a numerical study that includes the influence of different air speeds on the activity of the traditional still within the atmospheric conditions of Najaf City, Iraq.

2. THERMAL ANALYSIS OF THE MODEL

Figure 1 shows the model diagram presented in this work, which shows the equations of energy conservation. The model consists of a basin made of pure iron coated with a heat-absorbing black dye. The basin is wrapped from the bottom and all sides with a high-strength white cork material that works as (thermal insulation and is resistant to steam leakage). This fully insulated basin is placed inside a specially designed wooden container. A 32.1-degree inclined transparent glass lid is used to close the wooden structure from the top, allowing solar radiation to pass through it and reach the water layer to warm up and thus the basin plate to absorb it. The physical properties used in the simulation program of this model are described in Table 1 and Figure 2. Using the COMSOL V5.3 numerical simulation program, the study was conducted within the climatic conditions data of Najaf city, Iraq, for the day of (13/4/2024. Figure 3 shows the solar radiation and air temperatures for the day of (13/4/2024).

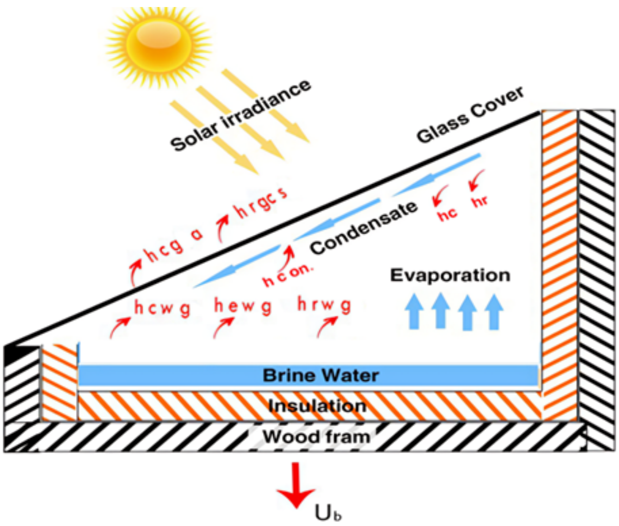

Figure 1. The simulation model used in this study is shown with energy conservation equations.

Table 1. The physical properties of the model used in the simulation program.

parameter	Value	parameter	Value	Parameter	Value
Hl(m)	0.2	$k_{ins}(w/m.k)$	0.03	$x_b\ (m)$	0.0015
Hr(m)	0.83	$x_{ins}(m)$	0.025	$\rho b\ (kg/m^3)$	7870
ε_g	0.88	$cp_w\ (J/kg\ K)$	4190	$\sigma(W/m^2\ K^4)$	5.669x10-8
τ_g	0.9	$A_w(m^2)$	1.0	ε_w	0.96
τ_w	0.95	$A_g(m^2)$	1.1987	$m_w(kg)$	10
α_b	0.9	$x_g\ (m)$	0.004	$\Theta(Degree)$	32.1
α_g	0.05	Cp_b (J/kg K)	460	$U_{ins,w}$ (w/(m² k))	0.5
α_w	*0.05*	$k_b(W/m.K)$	*73*	$X_{gc}\ (m)$	*1.1987*

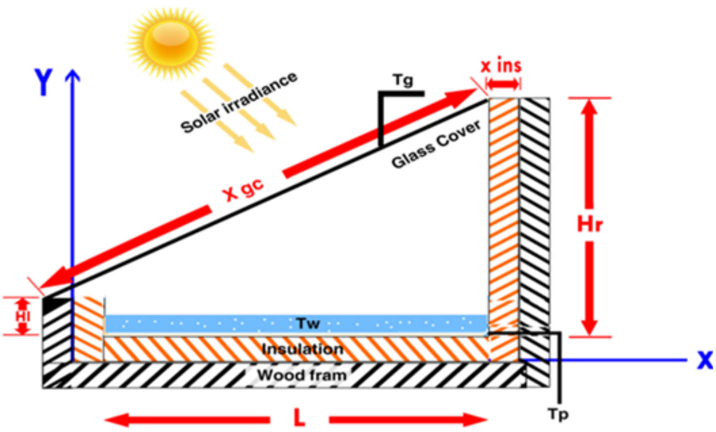

Figure 2.The model used in the numerical study is indicated by the most important dimensions.

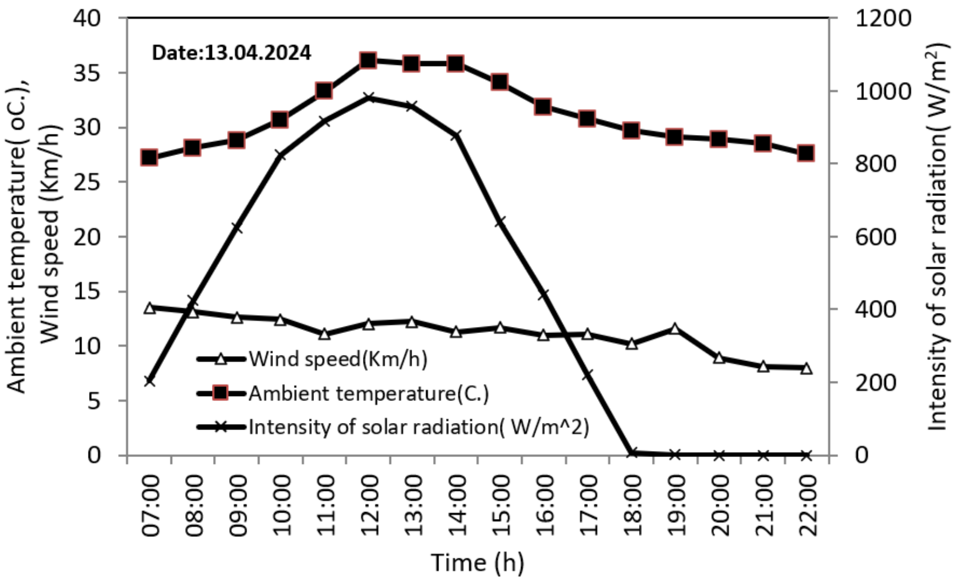

Figure 3. Actual values of real weather conditions used in this study.

3. MATHEMATICAL MODELLING

The mathematical analysis of the mathematical model has been carried out in two parts, the first of which applies energy conservation equations to all components of the model, and the other part is specific to the steam area. All equations are used after the following hypotheses are applied [19]and[20] :

1. The model is two-dimensional.
2. All flow inside the model enclosure is laminar.
3. No leak or escape of water or steam outside the model.
4. Except for the glass cover, there is no energy loss from the system parts to the surrounding area.

3.1. Energy conservation equations applied to all parts of the model [17],[21]

After the input of the physical specifications of the model, as well as the atmospheric values of Najaf city, Iraq (ambient temperature and solar radiation) over time, the computerized equations by COMSOL v5.3 were applied to obtain the results of the water basin temperature (T_w) and glass cover temperature (T_g).

Transparent cover:

$$m_g c_{p,g}\left(\frac{dT_g}{dt}\right) = A_g \alpha_g I + A_w h_{wg}(T_w - T_g) - A_g h_{rgs}(T_g - T_s) - A_g h_{cga}(T_g - T_a) \quad ....(1)$$

$$h_{wg} = h_{rwg} + h_{cwg} + h_{ewg} \quad ....(2)$$

Raw water:

$$m_w c_{p,w}\left(\frac{dT_w}{dt}\right) = A_w\left[I\alpha_w + h_{cbw}(T_b - T_w)\right] - A_w h_{wg}(T_w - T_g) - A_w U_{ins,w}(T_w - T_a) \quad ....(3)$$

Basin plate:

$$m_b c_{p,b}\left(\frac{dT_b}{dt}\right) = A_w\left[I\alpha_b + h_{cbw}(T_b - T_w) - U_b(T_b - T_a)\right] \quad ....(4)$$

After inputting the outputs of the first part (T_w and T_g), the equations of the second part are applied to obtain the yield value in hours and the total yield during the whole day.

Mass Conservation Equation:

$$\frac{\partial \rho}{\partial t} + \frac{\partial u}{\partial x}\rho + u\frac{\partial \rho}{\partial y}\rho + V\frac{\partial \rho}{\partial y} = 0 \quad .....(5)$$

Momentum Conservation Equations:

(i) x – direction momentum equation.

$$\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} = -\frac{1}{\rho}\frac{\partial P}{\partial y} + v\left(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2}\right) \quad ....(6)$$

(ii) y – direction momentum equation.

$$\frac{\partial v}{\partial t} + u\frac{\partial v}{\partial x} + v\frac{\partial v}{\partial y} = -\frac{1}{\rho}\frac{\partial P}{\partial y} + v\left(\frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2}\right) + F \quad ....(7)$$

Energy Conservation Equation:

$$\frac{\partial T}{\partial t} + u\frac{\partial T}{\partial x} + v\frac{\partial v}{\partial y} = \alpha\left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2}\right) \quad ....(8)$$

Concentration Equations:

$$\frac{\partial c}{\partial t} + u\frac{\partial c}{\partial x} + v\frac{\partial c}{\partial y} = D_{ab}\left(\frac{\partial^2 c}{\partial x^2} + \frac{\partial^2 c}{\partial y^2}\right) \quad ....(9)$$

The hourly and daily output of drinking water:

$$P_h = \frac{(-3600 \times D_{ab})}{L}\int_0^L \frac{dc}{dy}\Big|_{water} dx \quad ......(10)$$

$$P_d = \sum\nolimits_{24hrs} P_h \quad ......(11)$$

4. VERIFICATION OF THE SUBMITTED NUMERICAL WORK

The numerical work presented was validated by comparison with the T. Elango et al. [22] experimental study. The experimental work includes specifications such as basin plate 0.25 m^2, insulation thickness 38mm, and transparent cover 4 mm thickness at a 30 ° inclined angle. Figure 3 shows the comparison between the two studies.

Figures 4 and 5. show a comparison between the current study and the experimental study of T. Elango et al. [12].

We note a good agreement in the results as the error rate does not exceed 11% and 7% for the results of productivity and water temperature, respectively.

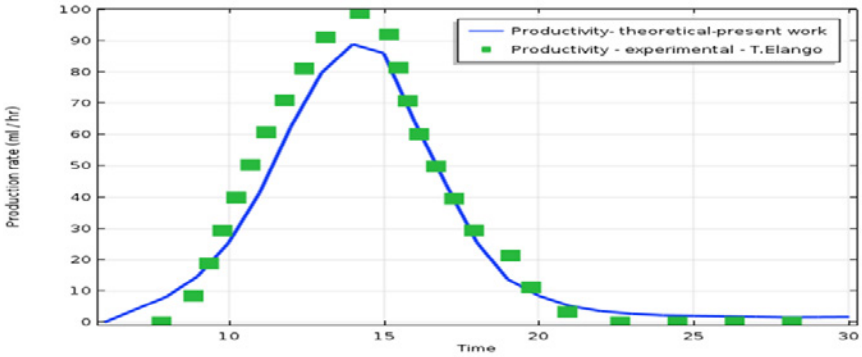

Figure 4. Comparing the present productivity theoretical results with [22] experimental results.

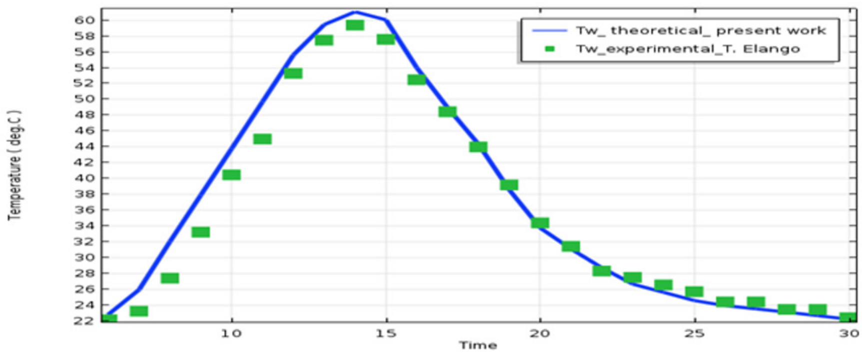

Figure 5. Comparing the present water temperature theoretical results with [22] experimental results.

5. THEORETICAL FINDINGS AND DISCUSSIONS

5.1. Effect of wind speed on the temperature of the glass cover

The theoretical study was conducted to determine the effect of increasing air velocity on the temperature of the transparent glass cover. Different values of air velocity were taken (0.5, 1.5, 3, and 4.5 m/s), and their effect on the glass temperature was studied over a whole day. When all other factors of the model are held constant, the temperature of the glass cover will decrease with increasing wind speed as a result of increased heat transfer from the glass layer to the surrounding area by convection, which increases the speed of cooling of the glass cover and vice versa. Figure 6 shows the effect of air speed on the cover glass temperature.

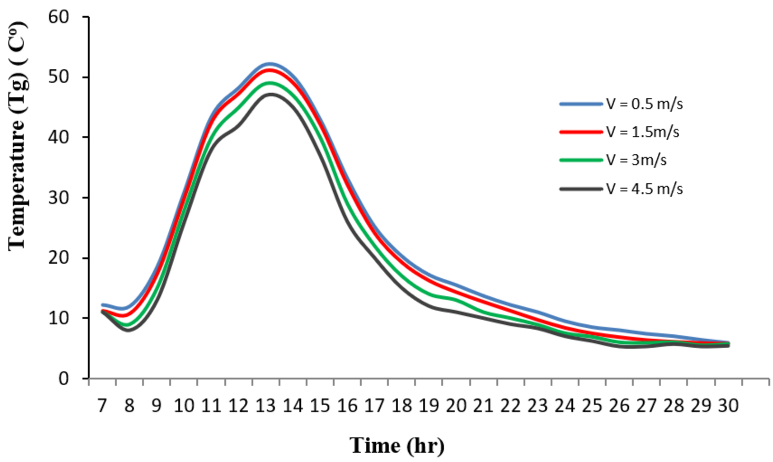

Figure 6. Effect of air speed on glass cover temperature.

5.2. Effect of wind speed on the vapor concentration within the model

Effect of wind speed on vapor concentration within the model

Through the simulation projections shown in Figure 7, we notice that when the speed of the air passing over the glass cover increases from 1.5 m/s to 3 m/s, the concentration of vapor inside the model can decrease significantly.

For example, at 11 a.m., we find that the average mass concentration of vapor has decreased from 11.3 moles to 9 moles due to the decrease in the temperature of the glass cover, which leads to an increase in the temperature difference between the glass cover and the raw water layer.

That leads to the vapor condensing in larger quantities on the surface of the glass, which increases the total productivity.

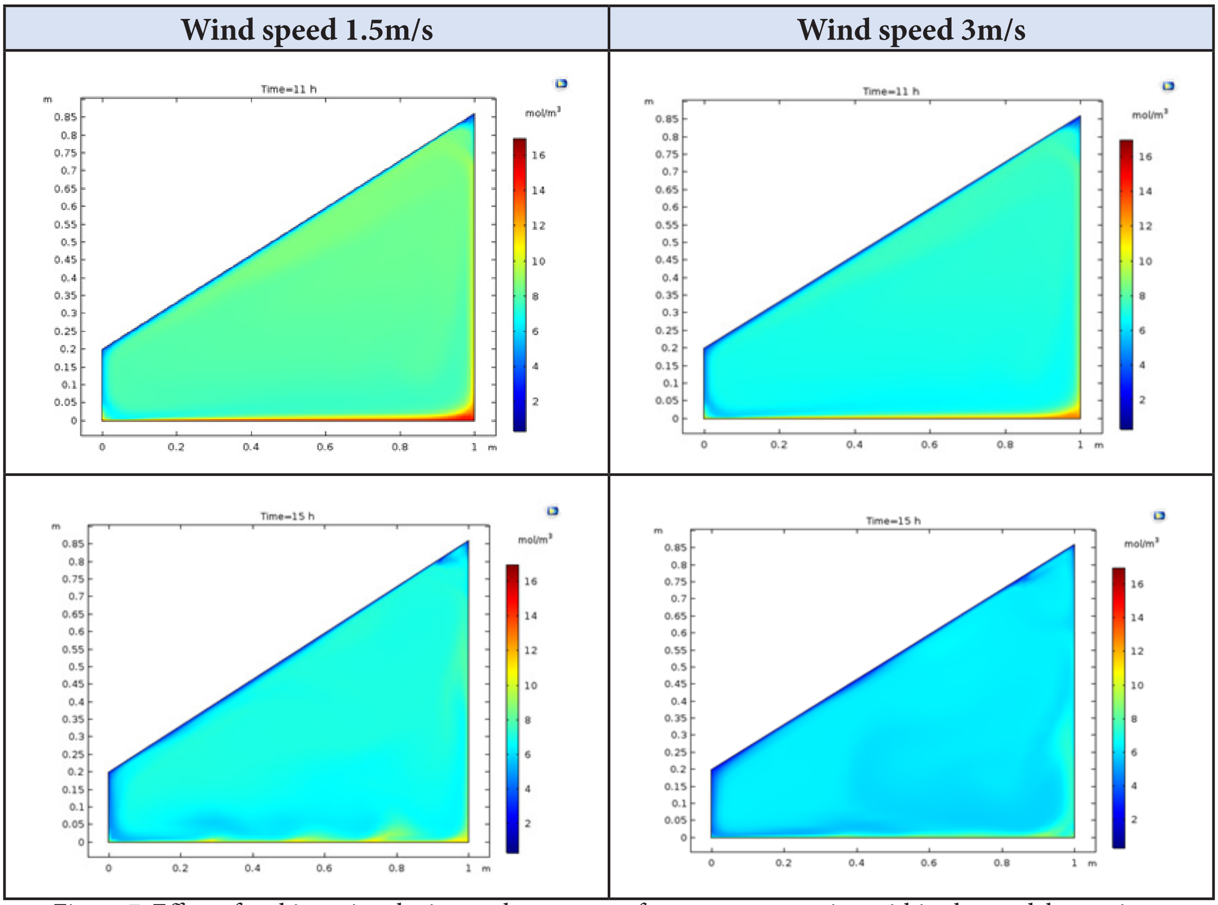

Figure 7. Effect of ambient air velocity on the amount of vapor concentration within the model over time.

5.3. Effect of wind speed on total productivity

The decreases in the temperatures of the glass cover as a result of the increased air speed increase the variation among the temperatures of the water layer and the temperatures of the transparent lid, which increases the amount of condensed steam significantly, and this is reflected in the value of the total productivity of the model. From Figure 8, the daily productivity of the model increases by about 4.7%, 10.3%, and 16% for air velocity (1.5, 3, and 4.5) m/s as compared to 0.5 m/s.

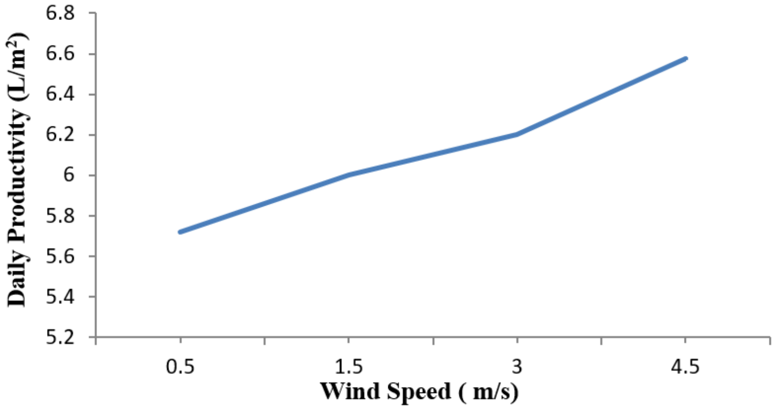

Figure 8. The effect of ambient air speed values on the daily productivity of the theoretical model.

6. CONCLUSIONS

The numerical study of the model provided by COMSOL V5.3 was conducted in the climatic conditions of Najaf City, Iraq. The results showed the following conclusions:
I. The increase in air velocity is inversely proportional to the glass cover temperature value.
II. Increasing air speed on the glass cover is inversely proportional to the amount of steam concentration within the model.
III. Due to the increase in the difference between the glass lid temperature and the water basin temperature, the productivity of the model increased.
IV. The value of the increase in air speed is directly proportional to the amount of daily productivity of the model, which increased by about 4.7%, 10.3%, and 16% for air velocity (1.5, 3, and 4.5) m/s as compared to 0.5 m/s.
V. The daily production value of the model is about 6 liters at 1.5 m/s.

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Data Availability Statement: Not applicable.
Conflicts of Interest: The authors declare that they have no conflict of interest.

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