Design and Fabrication of a Parabolic Trough Collector and Experimental Investigation of Wind Impact on Direct Steam Production in Tehran

H. Akhbari, M. Bidi, A. Bakhtiari, S. Eslami

Abstract—The present paper aims to the techno-economic feasibility of enhancing low-cost parabolic trough collectors in the light of developing the use of solar energy in under-developed regions where expensive high-tech solar devices cannot be afforded. Moreover, the collector is aimed to produce steam so that its performance is based on heat which can be discovered. In this regard, the manufacturing process and the detailed design models in Solidworks software are elaborated. Furthermore, the colletor's material is chosen in a way to minimize the costs. Finally, to assess the performance of the built collector, it is installed in the site of Shahid Beheshti University, Tehran, and the values of the effective peripheral parameters, such as temperature, wind speed, and most importantly, solar irradiance, are recorded simultaneously in June. According to the results obtained, the manufactured collector with the aperture area of 2 m^2 (1×2 m) is capable of producing 350 ml.h^{-1} steam. Also, the wind influence is comprehensively investigated in this paper. As a case in point, it was measured that as the wind speed maximized to 9.77 km/h, the amount of steam outlet is minimized to 580 ml.

Keywords—Direct steam production, design and fabrication parabolic trough collector, solar water heater, wind impact, experimental investigation.

I. INTRODUCTION

SUN is the source of all energy flows on the planet Earth. All the energy resources, either directly, or indirectly, relies on solar energy. For example, the electricity, which is produced in solar photovoltaic panels, illustrates the direct application of sunshine. In addition, the wind flow, which runs the wind turbines and helps produce electricity, is caused by the various solar radiation intensity on the Earth, and the resulting temperature gradient [1]-[5]. Solar energy, similar to any other renewable resources, is free and clean, however, there is one specific feature which sets solar energy apart from other resources; it is vast and almost anyone on this plant can benefit from it. According to the Renewable Energy Global Status Report 2015, solar energy shows the highest growth rate in terms of installed capacity all over the world in the period of 2009 to 2014 [6].

The collector is a device which converts solar radiation into a useful form of energy. In terms of application, solar collectors can be categorized into concentrating and non-concentrating collectors. Also, these collectors can be classified via their geometry and shape: flat plates, vacuum tube, parabolic trough and parabolic dish. Solar thermal collectors are those that collect heat content of solar radiation. In concentrating solar thermal systems, solar radiation hits the surface of the collector and then is reflected to the absorber tube through which the heat transfer fluid flows to absorb the heat of the reflected solar radiation [7], [8].

Steam production has always been crucial to various industries. For example, steam plays a crucial role in the chemical, food, wood, steel, textile, and water desalination industries [9]-[12]. In recent years, due to harsh worldwide water scarcity and climate change effects, assorted researches are conducted to elaborate on solar thermal systems and their application in steam production in water desalination units. In this regard, Rodriguez et al. [13] have economically evaluated the application of direct steam generation via solar parabolic trough collectors in a Multiple-effect distillation (MED) unit. In their configuration, water is the heat transfer fluid which flows through the solar field and drives the MED unit. In their study, the difference between conventional and solar MED units are investigated and different parameters, such as plants capacity, performance ratio and annual average freshwater production per square meter of the solar collector, have been taken into account. They have come to the conclusion that two parameters, namely energy cost and the cost of the solar collector are the most determining parameters that influence the condition of MED plants. Szacsvay et al. [14] have theoretically and experimentally investigated the performance a multi-stage flash distillation (MSF) unit coupled to a solar pond as the heat source. Furthermore, economic assessments have been done for the North African climate condition. Results indicate that in the case of increased unit size and serial production, the high cost of potable water in small units will be reduced. There is also a variety of researches conducted about different methods of manufacturing solar thermal collectors, especially parabolic trough collectors. For instance, Zou et al. [15] have experimentally investigated a small-sized parabolic trough collector for water heating in cold area of China. They have found that the thermal efficiency of the proposed PTC[1] reached about 67% even under the condition of solar radiation of less than 310 W/m^2.

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[1] Parabolic Trough Collector

There are obstacles preventing the development of such collectors, such as design problems regarding superheated steam production within the receiver tube and the costs of material and manufacturing procedures. The use of superheated steam as working fluid reduces the operating and maintenance costs of the collector, however, it leads to much more thermal stress in receiver tube due to its less convective heat transfer ability in comparison with oil and water [16], [17]. Eck et al. [18] have found that the maximum temperature gradient occurs at sections along the absorber tube where superheated steam is produced. Regarding this problem, they have observed that the maximum temperature gradient can be reduced by increasing the mass flow rate. Almanza et al. [19] have experimentally studied the behavior of parabolic trough receivers in a direct steam generation. In their experiments, they have observed deflections in steel receiver tube due to the centrifugal temperature difference. They concluded that the copper tubes show much less deflection to the temperature difference, and this is because of its higher thermal conductivity (appx. 7 times more). Avadhesh et al. have built a PTC for air heating. In their experiment, they have found out the thermal performance of various reflectors stainless steel sheet. [20]

The economy is the most prominent parameter determining the amount of progress of PTC industry. The lower the collector cost the more the commercial development is. Unfortunately, not many attempts are made in order to lower the cost of such collectors and costs are still in the order of thousands of dollars. For example, Chafie et al. [21] have manufactured and evaluated a PTC with an aperture area of 10.8 m^2. In their project, the thermal efficiency of the manufactured PTC is 55.1% and the sum total price is found to be 4346$.

Iran is located in the heart of the Middle East where solar energy potential is abundant. With more than 280 sunny days on over 90% of its territorial land, Iran is estimated to receive 1800 to 2200 kWh/m^2 per year, which is clearly higher than the global average. In recent years, there have been several thorough studies regarding the application of solar energy and its challenges in Iran [22]-[27]. However, these studies are mainly focused on PV applications. Marefati et al [28] have theoretically and experimentally analyzed the thermal performance of a solar collector of a parabolic trough type for the production of thermal energy in separate weather patterns in Iran with a comparison between the conventional nanofluids. Yaghoubi et al. [29] have an analysis of the heat losses of the absorbers tube of PTCs of Shiraz solar power plant.

In the present study, a lab-scale PTC has been designed and fabricated considering the problems of high-cost materials and manufacturing and design problems. For that, it has been tried to keep the fabrication cost as low as possible. In addition, to overcome the problem of thermal tension related to superheated vapor production, a design of the receiver tube has been presented. To evaluate the performance of the collector, experiments have been done at the Shahid Beheshti University of Tehran in July and under different environmental conditions such as radiation, temperature and wind speed. Outlet water temperature has been measured at the same time intervals and for different flow rates.

II. GOVERNING EQUATIONS

Each parabolic collector is made up of two main parts:
1. The concentrator in the form of a concave mirror, generally made of glass or polished steel plate.
2. Absorber tube comprising a metal tube with or without glazing.

In designing a collector all important properties such as component's material properties, optical and thermal specifications should be considered. One of the parameters that play a very important role in the collector's performance is its concentration ratio which is defined as [30]:

$$C = \frac{A_a}{A_r} = \frac{W}{\pi D_o} \qquad (1)$$

where A_a and A_r are collector aperture area and receiver tube area, respectively. To maximize the received energy, construction of collector with maximum concentration ratio is of particular importance. The maximum concentration ratio is calculated as:

$$C_{max} = \frac{1}{\sin \theta} \qquad (2)$$

where θ is acceptance half angle (Fig. 1).

The focal length of a PTC is calculated using:

$$y = \frac{x^2}{4f} \qquad (3)$$

where f is collector focal length, x is half the width of the collector and y is the depth of the collector.

Rim angle is the angle between the collector center line and the line connecting the rim of the reflector to the focal point. It is calculated as:

$$\varphi = \tan^{-1}\left[\frac{8(f/a)}{16(f/a)^2 - 1}\right] \qquad (4)$$

where a is absorber tube radius.

Collector radius can be found from:

$$r = \frac{2f}{1 + \cos(\varphi)} \qquad (5)$$

The best incident angle for parabolic collectors is 0.27 radian which is equal to half of the solar disk; and for this angle, the maximum concentration of 212 is achieved [31]. The amount of energy received from the Sun is different at different locations and different times of the year.
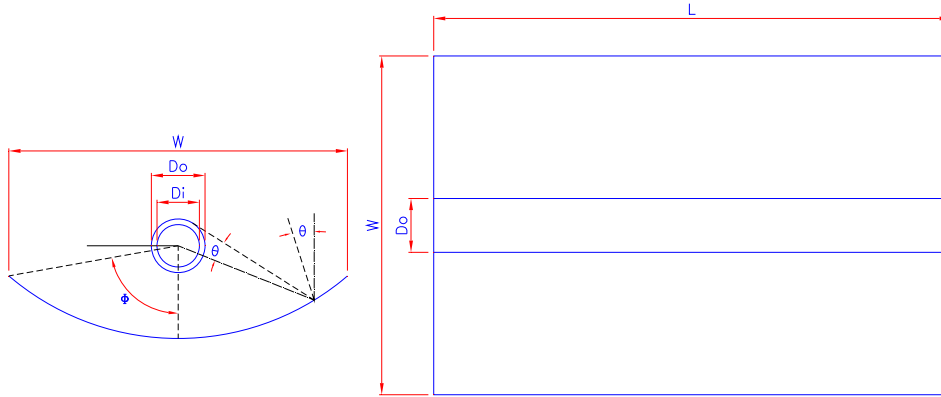
Fig. 1 Geometric specification of PTC

In the parabolic collectors, useful energy is the portion of solar radiation delivered to the heat transfer fluid [32]. Furthermore, useful energy is calculated using two different methods:

$$Q_u = F_R \left[SA_{ap} - A_r U_L (T_i - T_a) \right] \qquad (6)$$

where F_R is heat recovery factor and A_{ap} and A_r are collector aperture area and receiver tube area, respectively. These areas can be found from:

$$A_{ap} = (W - D_g) \times L \qquad (7)$$

$$A_r = \pi D_o L \qquad (8)$$

Also, the useful energy is calculated by:

$$Q_u = \dot{m} c_p (T_o - T_i) \qquad (9)$$

in which $\dot{m}$, c_p and T_o are respectively mass flow, specific heat capacity and the outlet temperature of the heat transfer fluid.

In (6), heat recovery factor is calculated as:

$$F_R = \frac{\dot{m} c_p}{A_r U_L} \left[1 - \exp \left(-\frac{U_L F' A_r}{\dot{m} c_p} \right) \right] \qquad (10)$$

in which F' is collector efficiency factor and is calculated as:

$$F' = \frac{\frac{1}{U_L}}{\frac{1}{U_L} + \frac{D_o}{h_{fi} D_i} + \left[\frac{D_o}{2k} ln \frac{D_o}{D_i} \right]} \qquad (11)$$

hfi is convective heat transfer coefficient between heat transfer fluid and receiver tube inner wall. U_L is overall heat transfer coefficient and is calculated as:

$$U_L = \left[\frac{1}{h_r} + \frac{1}{h_w} \right]^{-1} \qquad (12)$$

h_r and h_w are radiant heat transfer coefficient and convective heat transfer between the receiver tube outer wall and ambient air, respectively.

III. DESIGN AND FABRICATION OF THE COLLECTOR

Regarding the acceptance half angle to be in the range of 0.3 and 0.5 radians, the value of 0.4 radians is selected. Receiver tube diameter is calculated as 0.0127 m and also according to (1), the concentration ratio is found to be 20.061 regarding the receiver tube diameter and collector width.

Usual value of the rim angle is between 70-110 degrees; values lower than 70 degree reduces the aperture width and the collector working temperature while the quantity higher than 110 degrees will increase reflective area without increasing the effective area [30]. All geometric characteristics of the mentioned collector are shown in Table I.

TABLE I
GEOMETRIC SPECIFICATION OF THE DESIGNED COLLECTOR

Item	Notation	Value	Unit
Width collector	W	0.8000	m
Half the width of the collector	x	0.4000	m
Depth of collector	y	0.2000	m
Absorber tube diameter	d	0.0127	m
Absorber tube radius	a	0.0064	m
focal length	f	0.2000	m
Rim angle	φ	75	degree
Reflecting mirror maximum radius	r	0.41	m
Half angle of acceptance	θ	0.0318	rad.
Concentration ratio	C	20.0612	-

In order to achieve the maximum solar radiation by the collector, the diameter of the receiver tube is selected small so as to increase the concentration ratio.

To oppose the problem of receiver tube deflection due to thermal stress, a design for the receiver tube is proposed to prevent changing the heat transfer fluid into superheated vapor. For that, a U-shape receiver tube has been made. The copper receiver tube is designed so that by using one collector we can use the radiation energy of two collectors.

The receiver tube length is 4 m, 2 m forward & 2 m route back. This increases the time of the fluid flowing through the receiver tube so the fluid temperature will increase dramatically. The receiver tube used in the present collector is shown in Fig. 2.

In order to lessen the distance between the tubes in a way

that the focal line does not pass through the receiver tube and thus prevent the loss of radiation, tubes have been attached to each other using a regular wire at same intervals.

Fig. 2 Connection point of the U-shape receiver tube

The receiver tube has been covered by black polyurethane (PU) coat which has high wear resistance and high stability against sunlight, humidity, and chemicals. Black color has a high absorption coefficient so it helps to increase the heat transfer rate. Water as the heat transfer fluid enters the copper receiver tube, absorbs the heat and then leaves it. This collector is one of the easiest methods of direct steam production but what puts the use of applicability of this system in doubt is the inability to control the water-vapor mixture in the receiver tube. In order to overcome this issue a 2% slope is considered in the receiver tube direction in comparison with the focal line.

Holding structure of the reflector is a very important part of PTC. In this model, polyethylene and polypropylene sheets are used to construct a favorable structure.

Solidworks model of the present collector is shown in Fig. 3. Nuts and bolts are used for connecting components and columns.
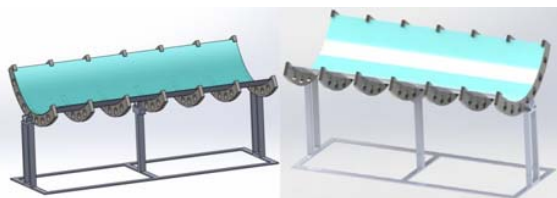

Fig. 3 Schematic design of collector by Solid works software

To compare the present collector with others, some of its bold features are:
- Simplicity of construction
- Lightweight and portable structure.
- Easy installation
- Removing of welding operation of structures
- Removing of thermal effects and thus deformation due to thermal stress
- Good resistance against wind forces.

In order to prevent errors in the orientation of the solar collector due to wind force acting on the collector, a lock has been designed.

Considering the sun movement, the present collector is designed to be able to track the sun. The tracking mechanism provided in this collector is manual by which the collector's aperture plane normal vector can be adjusted in 15-degree

intervals.

Fig. 4 shows the collector fabricated and installed in Shahid Beheshti University. It should be mentioned that the total cost of the collector is found to be 420$ which is fairly low in comparison with recently manufactured collectors in this range of performance.

IV. EXPERIMENT

The last step in designing the collector is to test its performance under different environmental conditions. To measure the environmental factors such as solar irradiation, ambient temperature, and wind speed data have been recorded using the facility of Renewable Energy Laboratory located in PWUT[2] campus, Shahid Beheshti University.
- To measure the solar irradiation Sunny Sensor Box RS485 has been used.
- To measure the ambient temperature Sunny Sensor Box RS485 has been used being able to measure ambient temperature in the range of -25 °C to +70 °C.
- To measure the wind speed Windsensor-IEN101010 has been used being able to measure wind speed in the range of 0.8 m/s to 40 m/s with an accuracy of ±0.5%.

To measure the water outlet temperature, Iskara thermocouple model ODTO0302 has been used which is able to measure the temperature ranging -220 to +800 °C. Water outlet temperature and volume have been measured every 15 minutes. Experiments have been done between hours 10:00 to 15:00 on July the 11th and 12th 2015 in PWUT campus.

In all experiments, it has been observed that water vapor exits the receiver tube in environmental conditions.

V. RESULTS AND DISCUSSION

Environmental data and collector results are shown in Figs. 4-7. Results indicate that steam production rate is directly proportional to the amount of solar radiation and as can be seen in Figs. 4 and 6, they obey the same trend. For example, maximum steam production on the day 192 happens when the ambient temperature is high and thus less thermal loss occurs. It should be mentioned that the liquid-vapor mixture generated in the collector is not two-phase mixture at saturation conditions hence the vapor and liquid temperatures are surely below the saturation temperature at the experiment location ambient pressure.
- In the present study, a small-sized PTC has been designed and fabricated regarding the problems of high-cost materials and manufacturing procedures and design problems.
- In addition, to overcome the problem of thermal tension related to superheated vapor production, a design of the receiver tube has been presented. To evaluate the performance of the collector, experiments have been done at the Shahid Beheshti University of Tehran in July and under different environmental conditions such as radiation, temperature and wind speed. Outlet water temperature has been measured at the same time intervals

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and for different flow rates.

- To oppose the problem of receiver tube deflection due to thermal stress, a design for the receiver tube is considered to prevent the heat transfer fluid changes into superheated vapor. For that, a U-shape receiver tube has been made. The copper receiver tube is designed so that by using one collector we can use the radiation energy of two collectors.
- Results revealed that a 1 x 2 m PTC located in Tehran is able to produce steam by the rate of 350 ml.h^{-1} under atmospheric pressure and without using a cover on the receiver tube.
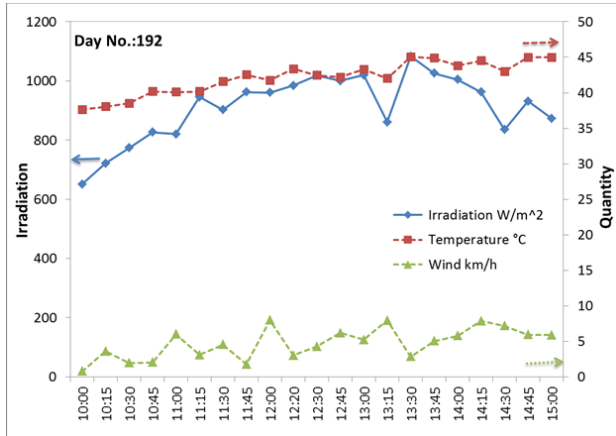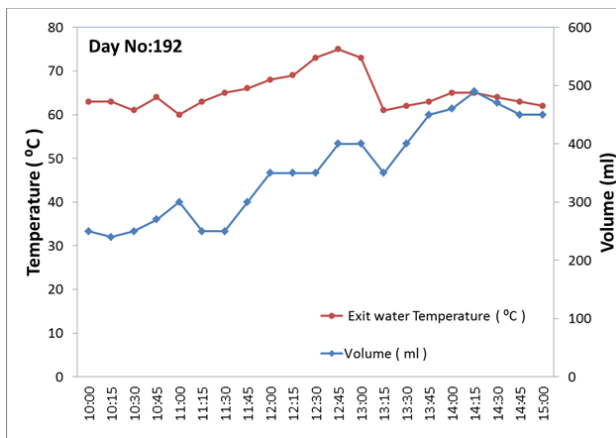

Fig. 4 Environmental data of day 192

Fig. 5 Obtained results in day 192 comprising water outlet temperature and volume

Fig. 4 depicts the collector's performance in heating up the heat transfer fluid on the day 192, which is July 11. As can be seen, in the time period of 13:00-13:15 and 14:00-14:30, ambient temperature and solar irradiation intensity have sharply decreased which is according to our observation due to the passage of clouds and increasing wind speed. The impact of this phenomena is clearly observed in Fig. 5 which shows the volume and the temperature of output water which is decreased in the mentioned time spans. This observation

directly implies the high influences of wind speed on PTCs without covers on their absorber tube. This happens because of cloudy weather. At the same time, the temperature and volume of outlet water gradually decrease. This effect is due to the lack of uncovered glass on the absorber tube.
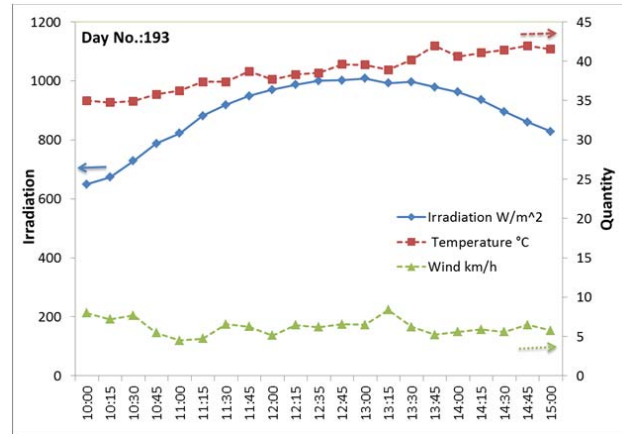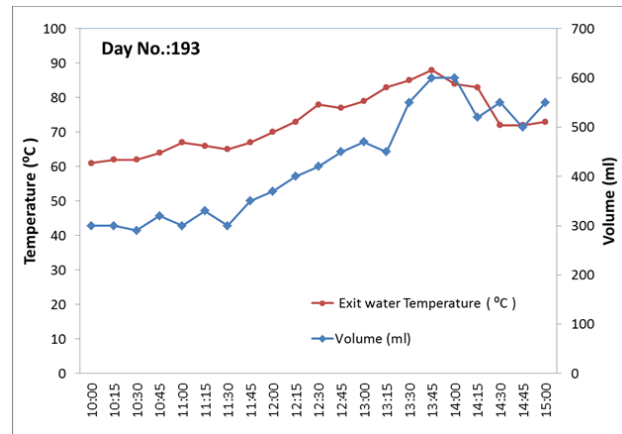

Fig. 6 Environmental data of day 193

Fig. 7 Obtained results in day 193 comprising water outlet temperature and volume

On the second day of the experiment, recorded environmental and the measurements data are respectively shown in Figs. 6 and 7. Both graphs decrease proportionally at 10 A.M. At this time, irradiation, temperature, and wind speed have been reported 649.25 w/m^2, 34.98 °C and 7.98 km/h, respectively. Simultaneously, in Fig. 7 water outlet temperature and volume have been recorded as 65 °C and 300 ml. Also, it has a sensible drop in both temperature and the amount of hot water outlet at 1:15 p.m. which is the result of an increase in the wind speed from 6.39 to 8.48 km/h. Fig. 6 also shows the amount of measured environmental parameters, such as solar irradiation, wind speed, and ambient temperature on July 12 (day 193).
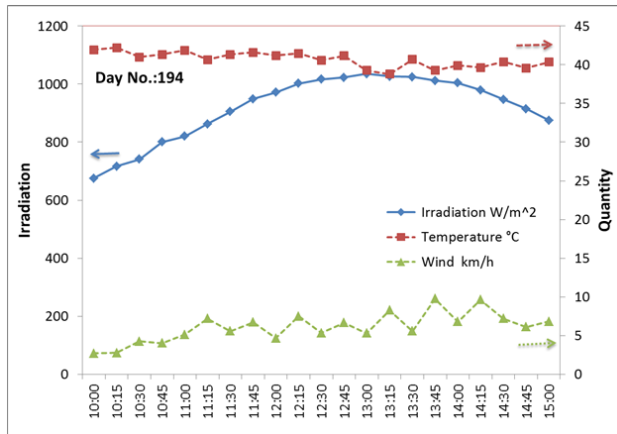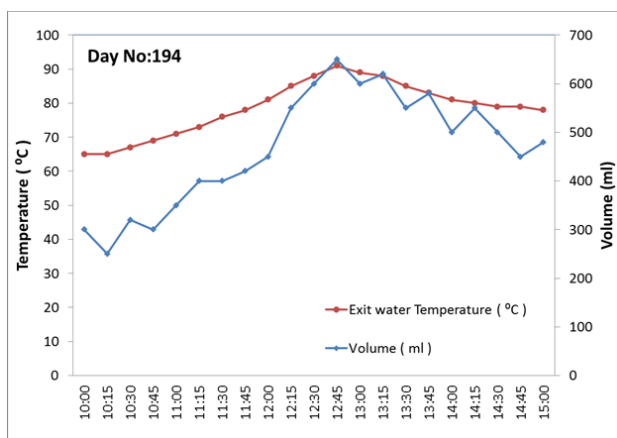
Fig. 8 Environmental data of day 194

Fig. 9 Obtained results in day 194 comprising water outlet temperature and volume

In the third day of the experiment, Fig. 8 is one of the most tangible line graphs to prove the effect of wind speed which is 8.28, 9.77 and 9.65 km/h respectively at 1:15, 1:45 and 2:15 p.m. In the following, the amount of vapor has rapidly changed in Fig. 9, respectively 550,500 and 500 millimeter.

Fig. 8 shows the results in the third day of the experiment which significantly proves the effect of wind speed. Wind speed change from 8.28 to 9.65 and the amount of vapor change from 550 to 500 in the same irradiation.

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