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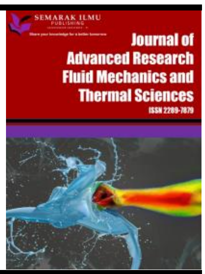

Investigation of the Effectiveness of Small Scale Solar Updraft Tower using Solar Simulator

Mohd Noor Asril Saadun[1,*], Nor Azwadi Che Sidik[2], Mohd Afzanizam Mohd Rosli[1]

[1] Fakulti Teknologi dan Kejuruteraan Mekanikal, Universiti Teknikal Malaysia Melaka, Hang Tuah Jaya, 76100 Durian Tunggal, Melaka, Malaysia
[2] Universitas Pendidikan Indonesia, Bandung, Indonesia

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ABSTRACT

Unique solar thermal system comprises a solar updraft tower (SUT) power plant. Numerous outdoor experiments are conducted, but they have a number of drawbacks, including the necessity for a lengthy setup period, a substantial financial investment, the possibility that the results may be affected by the weather, and the inability to manipulate the ambient factors. In this study, a laboratory-scale prototype with a square collector measuring roughly 2.27 m^2 and a chimney height of 1.5 m was built. This research focuses on finding many essential parameters for a solar updraft tower system by giving a time-dependent real-time sensor readout. With the help of the internet of things (IoT), measuring and monitoring applications underwent pilot testing. The results indicate that as solar energy increases, the collector and chimney temperature and updraft velocity will also increase. Experiments conducted aided in the comprehension of the thermodynamic properties of the solar chimney power plant, serving as the foundation for the construction of a large-scale solar chimney power plant.

1. Introduction

Solar energy is projected to be the most environmentally friendly and sustainable source of energy in the future [1]. Therefore, solar heater collectors are currently employed to exploit renewable energy sources [2,3]. Numerous studies are interested in the thermal performance of various solar systems; solar distiller to increase heat input and yield rate [4]. Solar updraft towers (SUTs) are a type of solar-powered structure that consists of three major components: a chimney, a turbine generator, and a collector as illustrated in Figure 1. In a study that used simulation to determine the optimal geometry for the solar chimney, Saadun *et al.,* [5] discovered that a collector with a slope of 0 degrees and an entrance gap of 0.05 m improved the system's power output. Additionally, in 2020 Saadun and Sidik [6] revealed that the highest temperature differences are approximately 15 °C, and the highest pressure differences are approximately 0.6 kPa, through outdoor experiments. Al-Azawie *et al.,* [7] studied different absorber materials numerically and

* *Corresponding author.*
E-mail address: asril@utem.edu.my

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validated them with experiments to determine the best material for the collector. Sifted sawdust and dark green painted wood were among the materials used to convert solar radiation to kinetic energy.

Numerous attempts have been made to measure instantaneous parameters, including meteorological and mechanical parameters, in order to investigate SUT performance as a unit system. Typically, resistance sensors, wind speed, a wind speedometer, and an anemometer are used to determine the airflow velocity within the chimney. For example, Ketlogetswe *et al.,* [8] utilised 11 sensors to monitor temperature, velocity, and solar irradiation, as well as a data logger to capture data for later analysis. Similar fashion, Buğutekin [9] used ten thermometers to determine the temperature of the air inside and outside the chimney, as well as five infrared thermometers to determine the temperature of the ground surface with data collection system collected and stored daily and 10 minutely intervals of time.

According to the literature reviewed above, an early concern in SCPP research was the interactive relationship between the extensive set of measurement devices and the SUT performance [10]. Ismaeel *et al.,* [11] revealed that as the number of skin and area of solar air heater in the collector increases, the system performance enhances. The air velocity at the base of the chimney is increased as the number of skin solar air heater in collector increased due to the lower thermal losses to the environment.

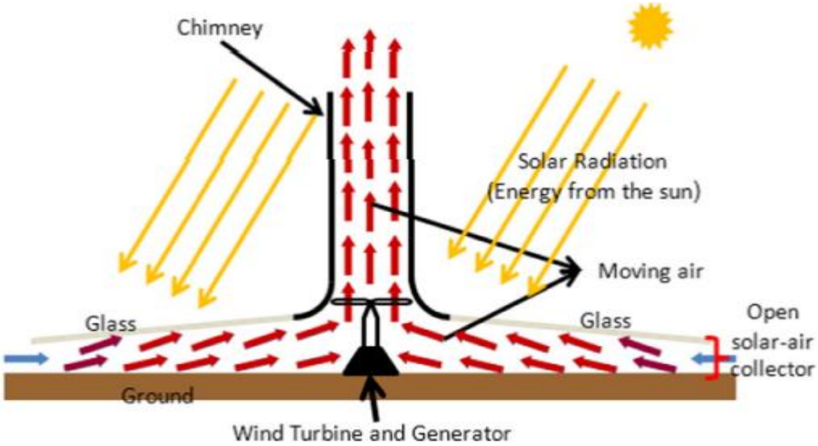
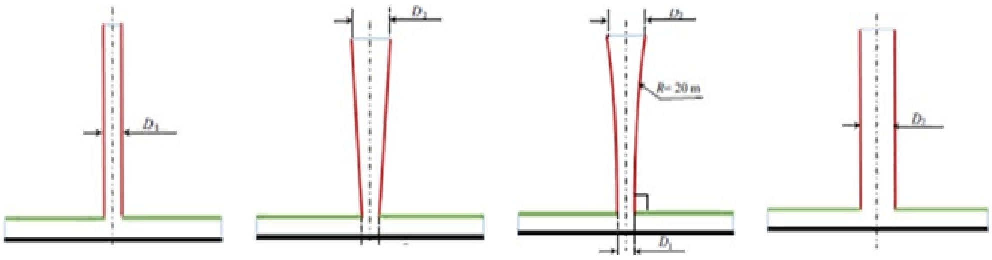


Fig. 1. Schematic diagram of SCPP

Al-Azawie *et al.,* [7] investigated numerically and experimentally various absorber materials under the collector. Sawdust, blackstone, ceramic, pebble, sand, and dark green-painted wood were utilized to transform solar radiation into kinetic energy. According to their analysis, ceramic is the most effective material at night. Mehla *et al.,* [12] conducted additional research utilizing various absorber materials, and he discovered that small stone pieces provided the highest average collector efficiency, collector exercise efficiency, and overall SUT efficiency. Using four distinct absorbers equipped with a convergent chimney, the experiment was designed to store the solar intensity and exchange it for the air being heated. Cottam *et al.,* [13] gave a significant examination and discussion of the optimal performance. In his unique study, the power production increases quadratically with the height of the chimney, confirming the necessity to build plants with tall chimneys. The optimization of the power output using the thermodynamic model and the cost model led him to the conclusion that numerous smaller power plants with a collector radius of around 3000 meters would be preferable than one larger power plant. Recent attempts have been made to approximate power output based on a list of household electrical appliances. Balijepalli *et al.,* [14] is generally described by the power plant's overall output. The tests were conducted over a 10-day period, and the results of one day were provided. The theoretical and actual outputs were 1.37 and 0.82 W, whereas the chimney and average plant productivity were 0.0187 and 0.0128 percent. A country like Malaysia receives seasonal weather with an average temperature between 26 °C and 29 °C throughout the year. In addition, the typical relative humidity and annual precipitation in this country are between 70 and 80 percent and 250 centimeters, respectively [15]. According to a study by Mohammad *et al.,* [16], the average monthly daily solar radiation in Malaysia ranges from 4000 to 5000 Wh/m^2. The monthly average of sunshine is between 4 and 8 hours, or roughly 2200 hours each year, and the highest daily maximum global solar radiation and direct normal radiation were recorded at 1068.10 W/m^2 and 915 W/m^2, respectively.

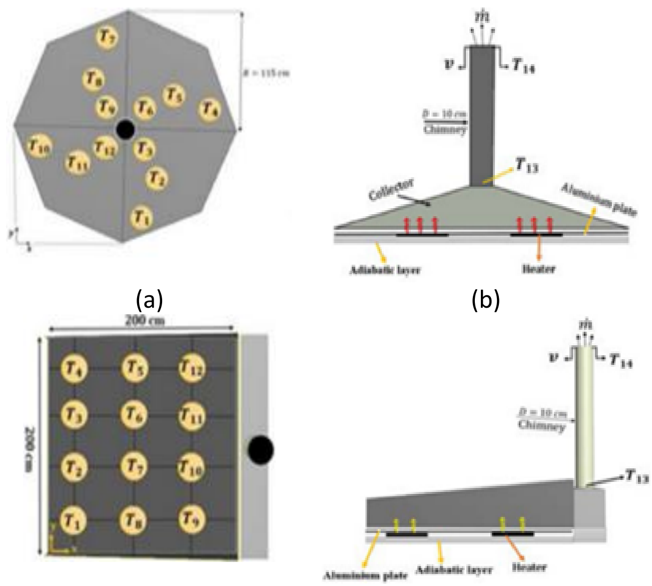
Nasraoui *et al.,*'s [17] findings indicate that the most effective solar chimney shape is the divergent chimney. Several simulations are conducted to evaluate the influence of the outlet-to-inlet diameter ratio (DR) on the chimney's efficiency; the results indicate that the efficiency decreases as the DR ratio increases. Different diameter ratio is illustrated in Figure 2 below.



(a) (b) (c) (d)

Fig. 2. Different DR ratio of chimney tower; (a) Cylindrical with a small diameter, (b) Conical, (c) Hyperboloid, (d) Cylindrical with a large diameter

The solar collector in SCPP functions as a heat exchanger, absorbing solar radiation and converting it to thermal energy before converting it to kinetic energy for the air in the collection as shown in Figure 3.



(a) (b)

(c) (d)

Fig. 3. Two different shapes of solar collector; Circular collector (a) top view, (b) side view. Square collector (c) top view, (d) side view

2. Methodology
2.1 Experimental Setup

In the Applied Solar Energy Lab (ASEL) at UTeM, a prototype solar chimney power plant of 1.5 m height and 2.27 m² in square shape was constructed. As shown in Figure 4, the chimney was fabricated from polyvinyl chloride (PVC) pipe (82 mm in diameter and 3 mm in thickness). For a prototype, it is important to determine a material with the main properties of light weight, high wind resistance, moisture resistance, and impact resistance [18,19]. In this study, PVC pipe was chosen due to its availability on the market, its durability, its outstanding thermal resistance, its less weight, and its flexibility during configuration. Due to space constraints in the lab, the diameter of the chimney should be small, and the chimney's height should not be excessively high to ensure its reliability for long-term use.

Fig. 4. Experiment test rig

The collector roof was supported by the collector base construction profiles that were firmly welded together. Reflection and absorption should be as low as possible for the collector, as well as a few other key material characteristics. To enhance the greenhouse effect in the system, the heat absorption via the collector material should be as high as possible, with high temperature and UV resistance 10 centimeters was discovered to be an appropriate distance between the ground and the edge of the collector to provide the ability for ambient air to enter the collector.

When conducting the experiment using solar simulator, several variables, such as solar radiation and chimney tower height, must be considered. The intensity of solar radiation must be determined based on the voltage supply to the halogen lamp, which is adjusted by a voltage regulator. The data for varied velocity and temperature at various collector sections need to be collected and recorded in order to determine their relationship.

In this project, the NodeMCU ESP32 microcontroller is used to computerize the monitoring system. Additionally, this system includes sensing devices for air temperature, moisture levels, pressure, and pH measurement. The temperature sensors for this experiment are stored in the collector and chimney. The chimney's starting entry is considered the most critical measurement point. Measurements are reportedly being taken of temperature, humidity and pressure. The arrangement of the thermocouples and hot-wire anemometer are illustrated in Figure 5. These valuable data is gathered from the sensors and processed in the microcontroller before being sent to the server database. Finally, as long as the internet is available, the data can be accessed via mobile or laptop. In this study, the pH value from the sensor does not necessarily significant due medium used in this solar thermal, which is considered normal air.

Fig. 5. The position of anemometer for velocity measurement

2.2 Solar Radiation Validation
2.2.1 Temporal instability

The temporal instability of the solar simulator must be examined to ensure that it is classified as class A or B in accordance with ASTM and IEC standards. The pyranometer is arranged outside to measure the sun's radiation for 1 hour and 30 minutes; radiation data is recorded every 10 minutes, and the experiment is repeated three times. Then, the radiation simulator must be on for 15 minutes to verify that the radiation is stable, after which a pyranometer is placed under the solar simulator to measure its radiation over the period of 1 hour and 30 minutes, and the experiment is repeated three times every 10 minutes. Figure 6 shows the experiment was executed for temporal instability.

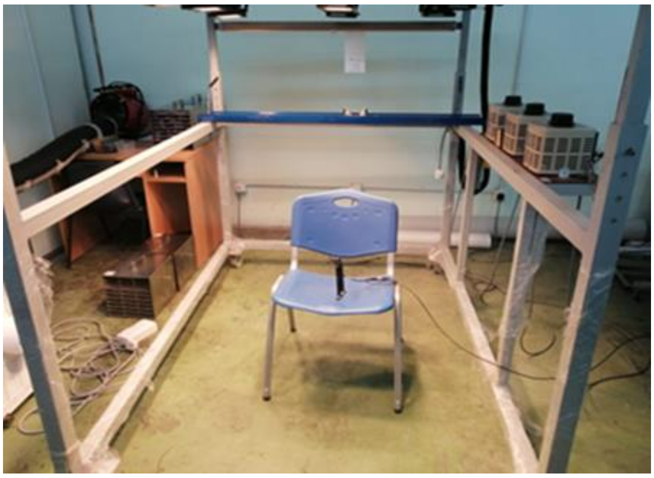


Fig. 6. Experiment for temporal instability

2.2.2 Spatial non-uniformity

To ensure that the solar simulator is classified as class A or B according to ASTM and IEC requirements, the Spatial Non-uniformity of the solar simulator has to be measured. The measurement area for solar radiation was divided into 64 rectangles, each measuring 14 cm by 20 cm. It was determined that the radiation remained constant throughout the testing process as Figure 7 due to the continuous electrical alimentation provided to the device. The solar simulator is turned on for 15 minutes to ensure that the radiation is stable, and then the radiation of each rectangle is measured by moving the pyranometer from the middle of one rectangular grid to the middle of another rectangular grid; the radiation of 64 rectangles is measured and recorded in detail. The entire area measured was 112 cm by 160 cm. Due to the generally continuous electrical alimentation, it was assumed that the radiation was consistent during the testing process.

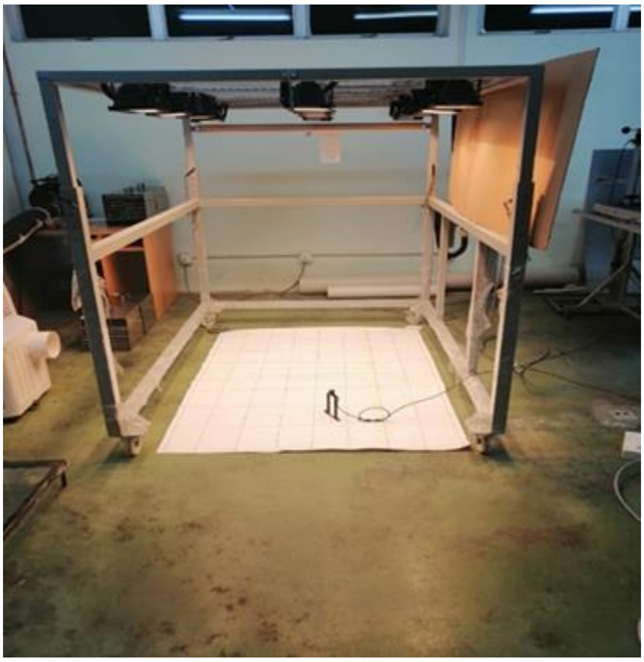


Fig. 7. Experiment for spatial non-uniformity

2.3 Difference Solar Radiation

Initially, the effect of solar radiation on the temperature and velocity of the air is investigated. Consequently, the voltage supply to the solar simulator is regulated using a voltage regulator to achieve five distinct levels of solar radiation: 200W/m^2, 300W/m^2, 400W/m^2, 500W/m^2, and 600W/m^2. After 15 minutes of operation, the pyranometer is placed beneath the solar simulator to measure solar radiation. After adjusting the voltage regulator to obtain 200W/m2 of solar radiation, the experiment test rig with a 1200mm solar chimney tower is positioned beneath the solar simulator for 30 minutes. The test is carried out using a thermocouple and hot-wire anemometers to measure the velocity and temperature of air. A thermocouple is used to monitor the air temperature at four distinct locations, while a hot wire anemometer is used to measure the air velocity and temperature at the chimney's entrance as illustrated in Figure 5. After thirty minutes, each point's air velocity and temperature are monitored and recorded. The experiment is then repeated with 300W/m^2, 400W/m^2, 500W/m^2, and 600W/m^2 using the same method. Charts were used to find out the correlation between the information gathered.

2.4 Difference Height of Solar Chimney

Another experiment is being conducted with the same solar radiation of 600W/m^2 but with solar chimneys of various heights of 1200mm, 1000mm, 800mm, 600mm, and 400mm. The solar simulator's voltage supply is controlled via a voltage regulator to 600W/m^2. In this case, 600 W/m^2 solar radiation is chosen as it is a maximum high-intensity solar radiation level as shown in Figure 8. After 15 minutes of operation, a pyranometer is placed beneath the solar simulator to monitor solar radiation. Then, the experiment test rig with a 1200mm solar chimney tower is positioned beneath the solar simulator for thirty minutes, and thermocouple and hot-wire anemometers are used to measure the air velocity and temperature. Each point's air velocity and temperature are measured and recorded after 30 minutes. The experiment is repeated with 1000mm, 800mm, 600mm, and 400mm using the same procedure. Charts were used to investigate the relationship between the gathered data.

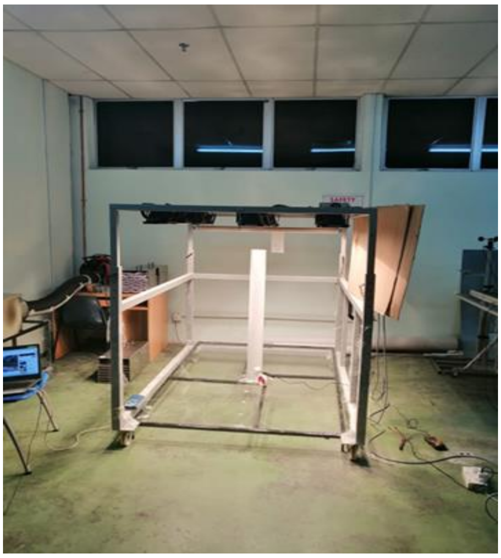


Fig. 8. Experiment with difference height of solar chimney

3. Results
3.1 Temporal Instability

It was necessary to determine the temporal instability of the solar simulator so that it could be compared to the actual sun's radiation. Every 10 minutes, the solar radiation over 1 hour and 30 minutes is measured using a Pyranometer. The solar chimney experiment must be conducted outside for an extended period of time, such as several days, in order to obtain accurate results. Every 30 minutes, the radiation of the sun throughout 5 hours and 30 minutes is measured using a Pyranometer.

According to Figure 9, the highest and minimum irradiance for the solar simulator for 1 hour and 30 minutes for Day 1 are 183.5W/m^2 and 179.5W/m^2 for Day 1, 185.2W/m^2 and 179.0W/m^2 for Day 2, and 182.8W/m^2 and 179.3W/m^2 for Day 3. Maximum and minimum irradiance for the sun along 1 hour and 30 minutes on Day 1 are 183.6W/m^2 and 133.1W/m^2, respectively. Maximum and minimum irradiance for the sun along 1 hour and 30 minutes on Day 2 are 305.6W/m^2 and 136.2W/m^2, respectively. As shown in the graph of radiation vs time, the radiation graph of the solar simulator is more stable than that of the sun. The temporal instability of the solar simulator is 1.1%, 1.7%, and

1.4% for those three days, which is less than 2 percent, hence the solar simulator is classified as Class A by ASTM and IEC.

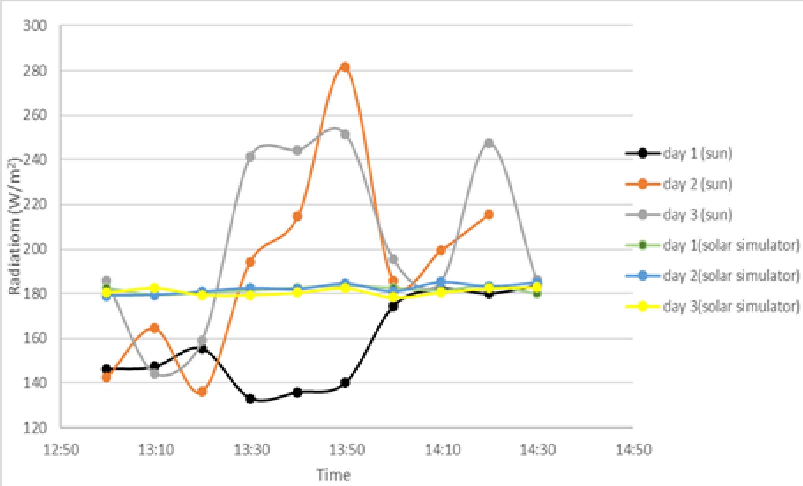


Fig. 9. Graph of radiation versus time for sun and solar simulator (long term)

According to Figure 10, the maximum and minimum irradiance of the sun for Day 1 along 5 hours and 30 minutes are 1376.5W/m^2 and 745.6W/m^2, respectively. For Day 2, the maximum and minimum irradiance are 1470.3W/m^2 and 640.3W/m^2, respectively. According to the graph of radiation vs time, the sun's radiation graph is extremely unstable. The temporal instability of the sun for Day 1, Day 2, and Day 3 is 32.4%, 39.33%, and 29.73%, respectively. This indicates that an outdoor experiment must be conducted over a long period of time, such as several days, in order to obtain an average result because solar radiation is highly unstable. Therefore, an indoor experiment is preferable to an outside one because it can save a significant amount of time.

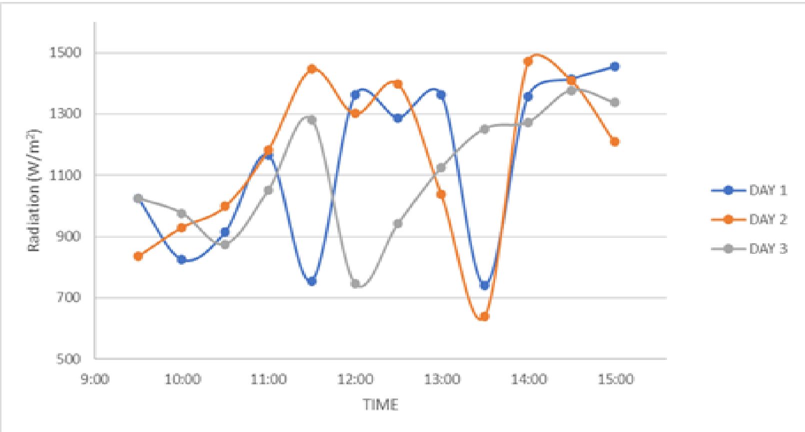


Fig. 10. Graph of radiation versus the time for sun (short term)

3.2 Spatial Non-Uniformity

To classify the solar simulator is classed as class A or B under ASTM and IEC standards, the Spatial Non-uniformity of the solar simulator had to be determined. The target area was divided into 64 rectangles, each measuring 14 cm wide and 20cm length. By moving the pyranometer inside the rectangular grid, the irradiation was thoroughly measured. In the center of each square, a pyranometer was placed. The total area that was measured was 112cm x 160 cm. Because of the generally continuous electrical alimentation, the irradiance was considered to be constant throughout the testing process.

The maximum and minimum irradiance for the solar simulator in the red colour zone is 113.5W/m^2 and 110.3W/m^2 according to Table 1. The Spatial Non-uniformity of the solar simulator is 1.5%, which is less than 2% according to ASTM and IEC. Therefore, the solar simulator is classified as Class A. In the yellow zone, the maximum and minimum irradiance for the solar simulator is 113.5W/m^2 and 102.7W/m^2, respectively. The spatial non-uniformity of the solar simulator is 4.99%, which is less than 5% according to ASTM and IEC standards. Therefore, the solar simulator is designated as Class B.

Table 1
Radiation of solar simulator under different area

	Radiation (W/m^2)							
	1	2	3	4	5	6	7	8
A	77.0	86.3	95.0	100.4	102.9	101.4	86.8	77.5
B	78.0	102.8	108.1	106.5	109.5	107.2	102.9	83.9
C	80.5	103.1	110.3	110.9	116.1	110.3	103.2	89.4
D	87.0	106.2	114.3	112.0	113.5	112.2	105.4	88.8
E	88.4	109.2	110.7	111.7	113.2	112.5	109.4	84.1
F	85.3	107.5	112.1	112.2	112.4	111.3	103.2	83.1
G	80.4	102.7	109.4	105.1	109.6	108.8	102.8	77.4
H	79.6	90.5	96.7	103.8	99.1	92.5	81.2	77.3

3.3 Difference Solar Radiation

Based on Figure 11, it is obvious that the velocity is greatest when the hot wire anemometer is placed 100mm above the bottom of the chimney tower; consequently, we can conclude that the optimal position for the turbine is 100mm above the bottom of the chimney tower, which corresponds to point 5. This sensor is used to detect the updraft velocity and temperature at the chimney, which are the most important parameters for evaluating the performance of SCPP due to the turbine of SCPP typically being located at this location. Due to the proximity of point 1 to the ambient temperature and the passage of cold air from the ambient into the solar chimney collector, point 1 has the lowest temperature compared to the other points. As the ground surface heats the air, the temperature rises along the flow direction until it reaches its maximum at point 3. Nevertheless, there was a slight decrease in air temperature at sensor 4. This is because to point 4's proximity to the chimney, which may prevent certain light rays from reaching this area, hence reducing the amount of radiation energy received. Based on Figure 11, it is clearly that when solar radiation increases, so does the temperature of the chimney and the collector. When solar radiation is 200W/m^2, the minimum temperature (point 1) is 27.81 °C and the maximum temperature (point 3) is 33.14 °C. However, when solar radiation is 600W/m^2, the minimum temperature (point 1) is 31.48 °C and the maximum temperature (point 3) is 39.32 °C.

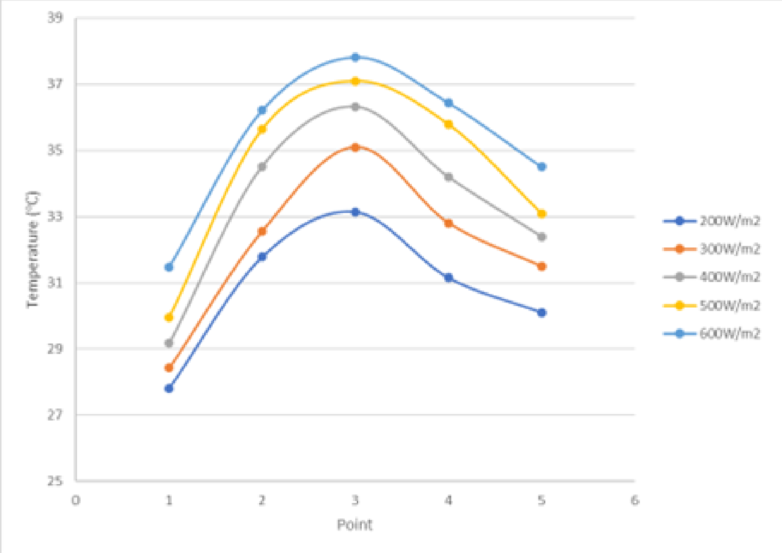


Fig. 11. Graph of temperature with different solar radiation (1200mm chimney height)

According to Figure 12, when solar radiation increases, the temperature rise also increases, which causes the updraft velocity to increase. The temperature increase for 200W/m^2 is 3,3°C, while for 600W/m^2 it is 7,7°C. Due to the increasing temperature difference between the interior and exterior of the solar chimney, ventilation is dramatically improved. The updraft velocity increases from 0.34m/s to 0.52m/s when the solar radiation intensity increases from 200W/m^2 to 600W/m^2. When solar radiation increases, the temperature in the collector and chimney as well as the updraft velocity rise.

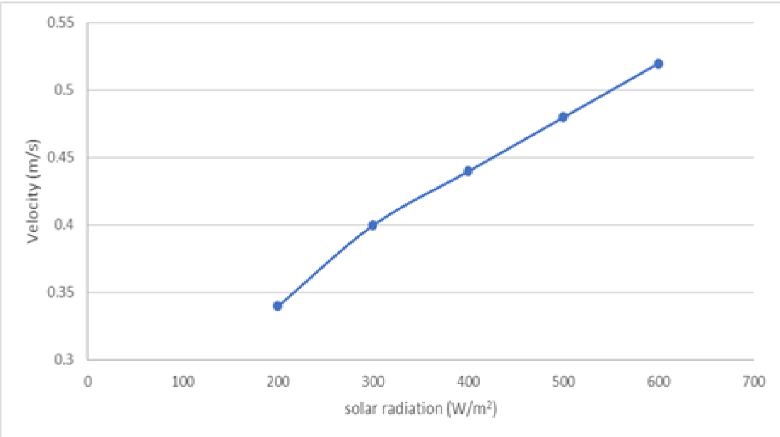


Fig. 12. Graph of velocity with different solar radiation (1200mm chimney height)

3.4 Difference Height of Solar Chimney

The standard component of a SCPP system is the chimney height, which has a significant effect on system performance, especially updraft velocity. As seen in Figure 13, the temperature at each point rises as the solar chimney tower rises in height. This is because the air trapped within the solar collector cannot be easily released. The effect of chimney height is complicated the total buoyancy force. On the one hand, the global buoyancy force varies with chimney height. An increase in the global buoyancy force generates an increase in the mass flow rate, which ultimately results in an increase in the collector temperature rise. When 1200mm of chimney tower is applied, the temperature rises by 7.7°C, however when 400mm of chimney tower is employed, the temperature rise is just 1.9°C. It is evident that when the height of the chimney tower increases, the buoyancy force and temperature rise also increase. As a result of the combined effect of a forementioned components, the trend seen in Figure 14 is exhibited by the curve. The updraft velocity increases with the height of the chimney, albeit at a decreasing rate. The trend of the experimental data indicates that the updraft velocity will never rise once the solar chimney tower reaches a particular height.

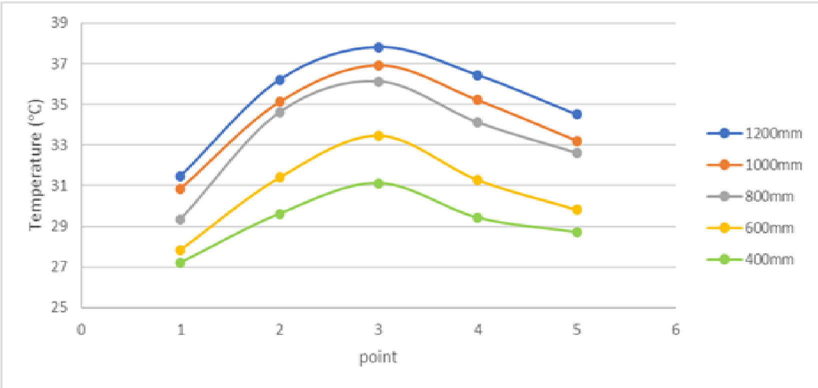


Fig. 13. Temperature with different height of chimney tower with constant radiation of 600W/m^2

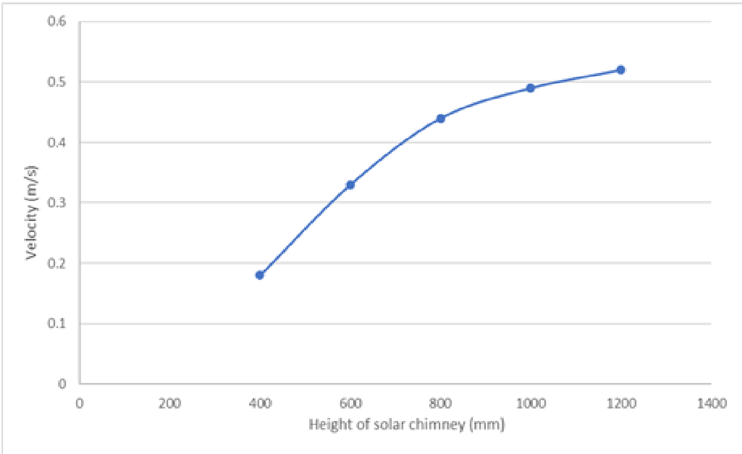


Fig. 14. Velocity with different height of chimney tower with constant radiation of 600W/m^2

4. Conclusions

This study aims to examine and comprehend the instantaneous performance of a small-scale solar updraft tower. The data indicate that the greenhouse effect occurred beneath the solar collector due to the temperature and pressure differential. These two major findings illustrate the system's ability to generate a buoyancy effect in the chimney, resulting in the expected updraft air. The velocity and temperature of a solar chimney power plant are influenced by the radiation and the height of the solar chimney tower; therefore, to develop the best performance of a solar chimney power plant, the location chosen for the solar chimney power plant must have high solar radiation and the maximum height of the solar chimney tower must be established. The greater the size of the solar collector, the greater the velocity at the chimney tower, and thus the greater the efficiency of the power plant.

In addition, performance of the experiment in a laboratory simulating an artificial environment demonstrates that humidity and wind speed are controllable and manipulable. Changing the diameter of the solar chimney tower is the next possible improvement; the dimension of the chimney tower is a potential factor for increasing velocity at the chimney tower.

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