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EXPERIMENTAL INVESTIGATION OF SOLAR VORTEX POWER GENERATION SYSTEM INTEGRATED WITH SENSIBLE THERMAL ENERGY STORAGE

Hussain H. Al-Kayiem[1*], Ali M. Tukkee[1], Nurul Fathonah Mohd Azid[1]

[1]Department of Mechanical Engineering, Universiti Teknologi PETRONAS, Malaysia

*Email: hussain_kayiem@utp.edu.my

ABSTRACT

Solar updraft power technologies suffer low efficiency and require a large collection area. Enhancement techniques are essential to overcome these setbacks. This paper investigates and discusses the effect of extended Sensible Thermal Energy Storage (STES) outside the canopy of the Solar Vortex Power Generation (SVPG) system. The extended sensible thermal energy storage integration is evaluated experimentally utilizing an SVPG model installed in the solar research site in Universiti Teknologi PETRONAS. The system consists of an (8-m-Dia). solar collector and a vortex generator. The selected material of the STES is black-painted pebbles that covered the ground underneath the canopy of the solar collector and then extended by 1 m outside the canopy. The variables considered for the performance evaluation are ambient, air inlet and outlet of the collector temperatures, incident solar irradiance, and air outlet velocity. Two cases have been studied, one with black painted pebbles covering the ground up to the outer diameter of the canopy (8-m-Dia) and the second is 1.0 m extended coverage outside the canopy (10-m-Dia). The performance of the SVPG is proven to enhance by the extension of the STES beyond the collector area. The extension of STES increased the mean thermal efficiency value by 0.85% and increased the mass flow rate by 0.01 kg/s. The performance indicator is increased by around 19.3%. It could be concluded that the extension of pebbles outside the canopy increases the amount of solar photothermic conversion, leading to improved efficiency of the SVPG system.

Keywords: *natural convection, photothermic conversion, sensible thermal energy storage, solar vortex engine, solar updraft power.*

INTRODUCTION

Solar energy is one of the methods widely used to pursue global environmental sustainability. After hydropower and wind power, solar energy is the third most important source of renewable sources. Despite that, the latest developments in research and technology have shown new insights on several solar thermal systems that could generate electricity; among them is the Solar Updraft Power (SUP).

Background and operational principles

SUP technology is based on three mechanisms, Solar Air Collector (SAC), stack effect due to buoyancy force and wind to energy conversion by a wind turbine. The solar energy is converted to thermal energy in the absorbing medium, usually ground in the collector. The heat is transferred by natural convection to air, which flows from outside the SAC and flows upward to the central part of the system. A wind turbine is installed at the base of the updraft unit and generates electricity. Up to the moment, SUP is embargoing two technologies, a Solar Chimney Power Plant (SCPP) and a Solar Vortex Power Plant (SVPP). In the SVPP, an artificial vortex replaces the tall physical chimney of the SCPP, which has greatly contributed to overcoming the high capital cost required to build the tall chimney. The operational principles of the SVPP, which is named

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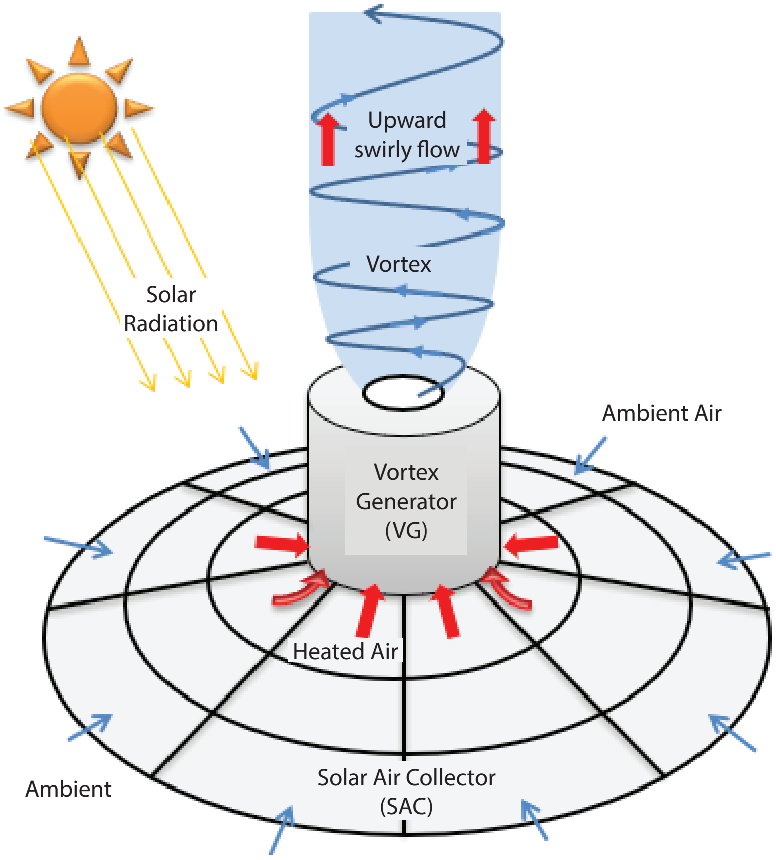

Figure 1 The layout of the solar vortex power generator [1]

as Solar Vortex Power Generator (SVPG) in the current article, are discussed and presented by Al-Kayiem et al. [1], as in Figure 1.

The technology of SVPG is developed based on the concept of the Atmospheric Vortex Engine (AVE) suggested by iSolarWorld [2]. The Split University – Croatia research team has developed mathematical modeling of the artificial vortex concept. Ninic and Nizetic [3] developed an elementary mathematical model of Gravitational Vortex Column (GVC) to replace the tall chimney. Then, an improved physical and analytical three-layer model of GVCs is reported by Nizetic [4].

Review articles institute state-of-the-art of artificial vortex for power generation concept. Mustafa et al. [5] presented and compared the convective and artificial vortices for power generation. Ismaeel et al. [6] reviewed the feasibility and potential of generating electricity by creating artificial vortices with and without a chimney. It was suggested that the industrial waste heat or solar vortex engine or integration of both concepts could be utilized for power generation applications. Nizetic [7] presented a state-of-the-art review on alternative energy concepts to produce clean, carbon-free electricity. The potentials of the proposed concept, such as a short diffuser, artificial vortex engine, its advancements over the decade, prospects and challenges were thoroughly addressed in the article.

SUP has the advantage of robust, low-temperature, low pressure and long life operational time. The disadvantages are the low efficiency and the need for a large ground area, which increases the cost of establishing such power plants. Therefore, a solution is to be considered to overcome this problem. This problem was solved by integrating SVPG with Thermal Energy Storage (TES).

Sarbu and Sebarchievi [8] have comprehensively reviewed and analyzed several technologies of TES and their mechanism in optimizing solar heat. In terms of solar collectors and thermal energy storage systems used for solar thermal applications, Tian and Zhao

[9] compiled different types of research. Powell and Edgar [10] conducted simulation studies where thermal storage systems show that the power plant's proportion of solar energy supply can be increased by as much as 47% to levels above 70% on a sunny day when adding 8 hours of storage capacity. Waked [11] has conducted a study on the ability of rocks to store solar energy. The study showed that rock storage could be successfully used for certain solar energy applications. One of its key benefits is that the rock pile's temperature is well stratified along its axis. Moreover, his study also showed a high possibility of recovering more than 60% of the energy stored in rocks at almost the full storage temperature.

Motivation

According to iSolarWorld [2], from several leading data sources, Germany has been a significant agency for using and generating solar power. Germany's total energy potential amounted to 47.72 GW at the end of May 2019. More than 50% of the country's daily demand for solar power energy has been met successfully. To put in comparison, Malaysia's main energy sources, with estimates of shares of 37% and 43% respectively in 2014, are petroleum and other liquids and natural gas [12].

Malaysia is one of the countries that remain underneath the sun perennially, with an average annual solar radiation of 1643 kWh/m^2 [13]. Therefore, solar power should be considered an alternative to fossil fuels in generating electricity. It has a promising potential for large-scale solar power plants. However, solar energy is still early due to the high cost of photovoltaic (PV) cells and solar electricity tariff levels [14].

There are only a few experimental data regarding the use of TES on a solar vortex engine. However, SVPG is still young, and data and system analysis lag are still early. More data is required to investigate its effect on the performance of such systems.

The main objective of the current study is to evaluate the SVPG performance by integration with sensible TES (STES) by experimental investigation. The TES used in this investigation is black painted pebbles covering the ground and functioning as solar absorbing, solar photothermic conversion, and solar thermal energy storing. Accordingly, the existing SVE model has been modified and tested under two cases. The first case is with TES diameter same as the canopy, while the second case is extended TES diameter to extra 1.0 m outside the canopy. The two cases have been compared, and the performance enhancement is presented in terms of the improved temperature difference and higher mass flowrate.

METHODOLOGY

The research method adopted in the current work is entirely experimental investigations. An existing model of SVE in Universiti Teknologi PETRONAS (UTP) solar research site was utilized to measure and evaluate the integration of STES with the SVPG.

Using black pebbles as the STES for this system could increase the heat transfer rate as the pebbles cover a larger area outside the canopy coverage area. The extension is 2 m larger in diameter than the canopy-covered area. Thus, a higher heat transfer rate would also achieve higher thermal efficiency. Furthermore, it would also be a possible method to reduce the cost needed in constructing a larger collector size. Therefore, this experimental study is carried out to examine the thermofluid parameters and the overall performance of the SVPG when the STES extended without a canopy.

Layout and description of the experimental SVPG model

The SVPG setup was established at the solar site in UTP, Perak, Malaysia, at a latitude of 4.37º N and a longitude of 100.97° E. The SVPG system consists of the SAC and the VG unit. In this study, pebbles painted in black are integrated into the system to act as a STES. The original setup was modified by extending the ground covered by pebbles beyond the collector radius by 1.0 m. Figure 2 shows the system after the installation of the STES.

The SAC is a component of a solar thermal system used to convert the solar radiation to thermal energy in the solar absorber medium and then convert it to kinetic energy in the air. Perspex is used and placed on the steel frame to act as a solar collector. Before placing the Perspex on the steel frames, a rubber seal and silicone are installed at the edges of the Perspex to close the gaps between the Perspex plates and the collector

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frame. This is crucial to prevent warm air from escaping to the surroundings and rainwater from penetrating inside the SAC, reducing the system's thermal efficiency. Perspex plates are then added to the system by placing them on the frame.

Based on the study done by Al-Kayiem et al. [15], which are the developer of the existing experimental setup, the thermal properties of the Perspex as a solar collector can be summarized in Table 1.

Table 1 Radiant Thermal properties of Perspex as collector cover [15]

Thermal Properties	Value
Emissivity,	0.9
Transmissivity,	0.92
Absorptivity,	0.06

The collector without extended STES is 8.8-m-diameter, and with the 1.0 m extended STES, the model becomes 10.8-m-diameter. The canopy has an 8.5° slop from the central to the outer peripheral of the collector. The inlet is around 150-mm- high.

The purpose of the vortex generator engine (VGE) is to produce updraft airflow in a rotational motion by extracting air from the base of the VGE and extending its upward above the engine. The aerothermal process in the VGE involves velocity and temperature. At the upper hole of the VGE, the vortex velocities are tangential, radial, and vertical components since the airflow have a 3D configuration. The VGE consists of two cylinders known as the inner and outer cylinder, as shown in Figure 3. The function of the inner cylinder is to impose rotational motion and direct the airflow to the upper hole of the VGE. The outer cylinder provides insulation to retain the heat captured from dispersing to the surrounding using fiberglass as thermal insulation. The inner cylinder has eight peripherally-lit entry slots to allow heated air to enter the VGE. A rotational motion of air takes place as the updraft airflow occurs. Therefore, eight adjustable vanes are installed between each entry slot inside the inner cylinder to direct the airflow to make the rotational motion. At the top of the VGE, a circular transparent Perspex covers the engine. The plate has a hole at the center of 0.3-m-diameter. The upper hole acts as the system's exit to the atmosphere in a vortex shape.

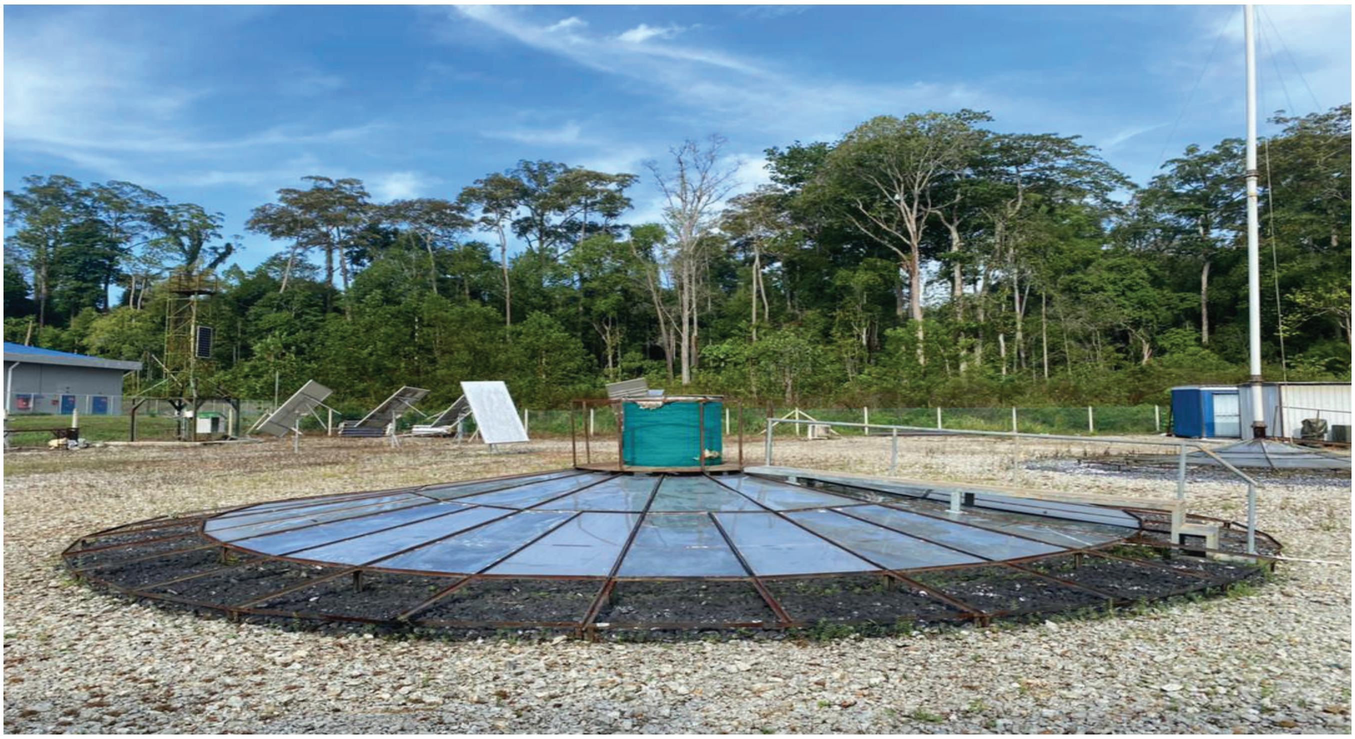

Figure 2 Solar Vortex Power Generation experimental model after completion with ground coverage by black painted pebbles

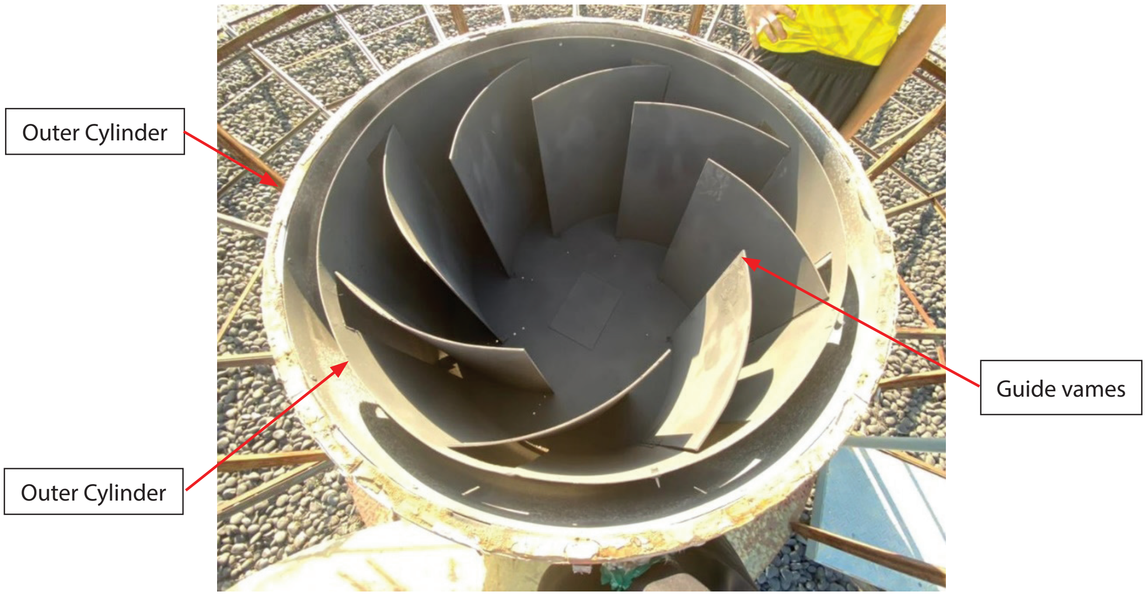

Figure 3 Internal configuration of the established VG

Measurements and instrumentations

The measured variables in this experiment are temperatures, air velocity, solar irradiation, and humidity. The temperature probe is placed at different points on the SVPG, as shown in Figure 4. The measuring instrument used is the Extech Model 45160 3-in-1 Humidity, Temperature and Airflow Meter. It has an accuracy of ±2.5°C ranging from –0°C to 50°C. The data obtained could be displayed directly on the device's LCD screen. The inlet temperature is measurements at 4 different locations of the circumferential of the canopy and is repeated many times at North, South, West and East. The average of the four readings is considered for calculations and analysis. The repeatability of measurement is to reduce uncertainty. Since the SVPG utilizes solar vortex, which is derived by warm air flowing from the solar collector into the vortex engine, the rate of airflow would be a crucial parameter to be

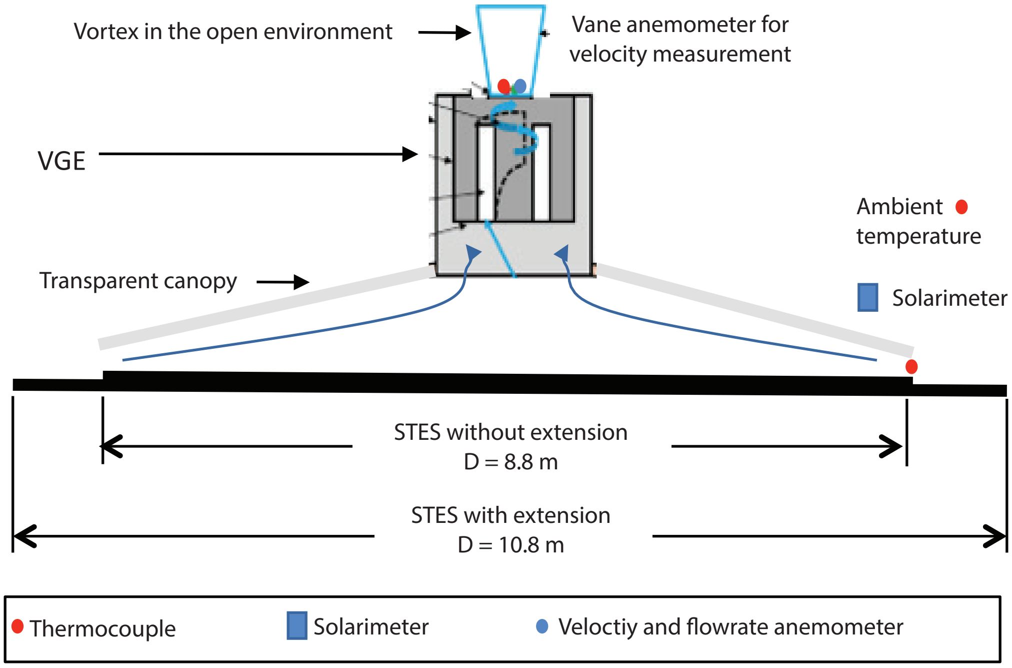

Figure 4 Schematic of the SVPG setup showing the locations of the measuring instruments

monitored and measured using a vane anemometer over a selected cross-section, such as the exit of the system, which is located at the top hole on the VGE.

Similarly, the measuring device used to record air velocity is Extech Model 45160. The device is positioned in two main directions on the top exit hole of the vortex engine. The two different directions measure velocity in the axial and tangential directions. The radial component is neglected as it is very small compared to the other components. The device is equipped with a built-in low friction vane wheel which helps to improve the accuracy of air velocity. The vane must be positioned perpendicular to the direction of airflow. Air velocity measurement is executed so that the vortex formed at the outlet has rotational motion. Thus, a resultant velocity could be calculated once the axial and tangential velocity measured, as:

$$V_{resultant} = \sqrt{V_{axial}^2 + V_{tangential}^2} \tag{1}$$

The most critical parameter for solar power systems is the incident solar radiation. The measuring device typically used for the incident solar radiation is a solarimeter that measures direct and diffuse combined solar radiation. For this project, a Solarimeter KIMO-SL 200 model is used to measure the solar insolation. It has solar irradiation ranging from 1 W/m² to 1300 W/m², a 5% measurement accuracy, and an operating temperature range from –10°C to 50°C.

The air mass flow rate could be estimated since the velocity and hole area are known, equated as:

$$\dot{m} = \rho_{air}\, A_{cross\ section}\, V_{outlet} \tag{2}$$

where, ρ_{air} = density of air (kg/m³), $A_{cross\ section}$ is the area of the upper hole, and V_{outlet} is the air axial velocity component at the outlet (m/s).

Performance analysis of SVPG system

The performance of the SVPG is presented in terms of thermal efficiency. Thermal efficiency is the percentage of heat energy converted into work. Several parameters and variables are taken for experimental measurement to calculate the thermal efficiencies. These equations are represented by the ratio of the collector's average heat output divided by the rate at which solar radiation strikes the panel, given as:

$$\eta_{th} = \frac{Q_{out}}{Q_{in}} = \frac{\dot{m} C_p (\Delta T_{air})}{I \times A_{collector}} \tag{3}$$

where, $\dot{m}$ is the air mass flow rate (kg/s) predicted by equation (2), C_p = Specific heat of air at constant pressure (kJ/kg·K), $\Delta T_{air} = T_{outlet} - T_{ambient}$, I = Incident solar radiation (W/m²), and $A_{collector}$ = Surface area of the collector (m²).

It is more reliable to consider performance indicator (PI) to compare between the solar updraft technologies. The recommended and used PI in this study compiles many parameters, including the exit air temperature, the velocity and the air temperature rise, as:

$$PI = \dot{m}\Delta T \tag{4}$$

Measurement procedure

The experimental measurements for the SVPG were taken for four days which are on 10th March and 11th March 2021, for the first condition: without pebbles extension, while the second condition takes place on 13th and 15th March 2021. This period included the basic runs and data collection for both conditions. For each condition, the measurement was repeated for two days to ensure fair accuracy of the findings. From 09:00 am until 04:00 pm, measurements were taken regarding the outlet velocity components, air temperatures at the outlet, and solar radiation. The average values of the data collected were used to analyze the results and their reasoning.

RESULTS AND DISCUSSIONS

This section summarizes results obtained during the data collection period for the experimental investigation of the integration of thermal energy storage in the SVPG system. The results consist of data compilation for both conditions: without extension and with an extension of ground covered by pebbles. Furthermore, thermal efficiency analysis for both conditions is also explained in this section. The thermal efficiencies and the effect of TES integration are compared and further discussed in this section's outcome.

Environment condition analysis

Measurement was taken on an hourly basis starting from 9:00 am to 4:00 pm, including the data of solar irradiation, temperatures at various locations, and the exit velocity at the upper hole of the VGE. The data collection period for the experimental measurements was divided into durations since there are two different tested STES configurations. The first duration was on 10th March 2021 and 11th March 2021, without the extension of pebbles. The second duration was on 13th March 2021 and 15th March 2021, where the STES has been extended beyond the canopy diameter. The peak and mean solar irradiance recorded for the 11th and 12th March are 1063 and 811.2 W/m², respectively, with no extended STES. For the 13th and 15th March measurements, where the STES has been extended, the peak and mean solar irradiance were 1053 and 798.6 W/m², respectively. The recorded mean peak ambient temperatures were 34.7°C and 34.6°C for the cases without and without STES extension, respectively.

In comparison, the mean ambient temperatures were 33.5°C and 33.1°C for the cases without and with extended STES, respectively. The experimental solar and ambient temperatures are very close for both cases of STES. Table 2 summarizes the average and peak measurements for solar radiation and ambient temperature during the experimental measurement durations.

Figure 5 describes the average solar irradiance and ambient temperature throughout the measurement days based on hourly basis recorded data from 09:00 am until 04:00 pm. The similarity in variation trends and close values of the solar and temperature conditions make it confident to compare the other parameters of the system in cases without and with extended STES. The solar irradiation is approximately 300 W/m² for STES cases. As it reaches midday, the solar radiation increases and reaches its maximum value between

Table 2 Mean peak measurements

Duration (STES configuration)	Mean peak solar irradiation (W/m²)	Mean peak ambient temperature (°C)	Mean solar irradiation (W/m²)	Mean ambient temperature (°C)
11 & 12 March 2021 (without extension)	1063.0	34.7	811.2	33.5
13 & 15 March 2021 (with extension)	1053.0	34.6	798.6	33.1

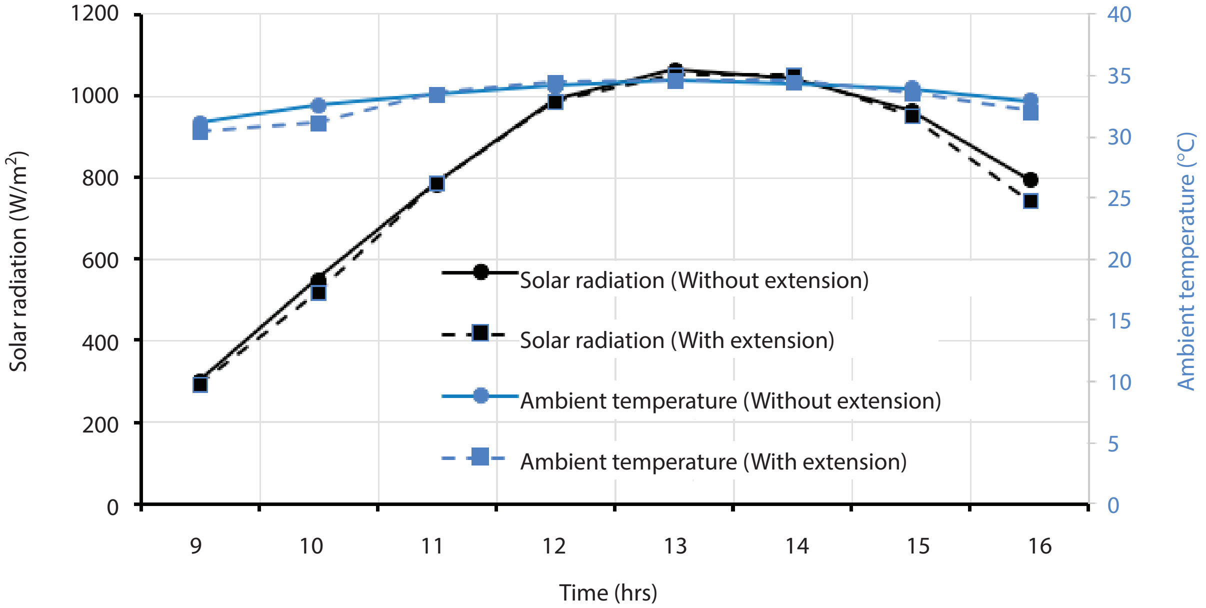

Figure 5 Solar radiation and ambient temperature throughout the data collection period for both conditions

01:00 pm and 02:00 pm. At the peak hour, the recorded solar radiation is 1063 W/m^2 without extension of the pebbles and 1053 W/m^2 with the extension of pebbles. The ambient temperature variation is slight within a range of 30.4°C to 34.7°C. Similar trends of solar and ambient temperature were reported by [16].

Thermal analysis

The thermal analysis of the system and comparison between the two tested cases is achieved by analyzing the working fluid temperatures and thermal efficiency. Air temperature rise is one of the main factors in successful SUP application. The air temperature rise is the difference between the air outlet temperature from the VGE and the ambient temperature. The measurement data of air temperature rise is presented in Figure 6. The trend of air temperature rise for both cases was a peak between 12:00 pm and 01:00 pm and gradually decreased after 02:00 pm. The behavior of the temperature rise has a massive effect on the system's thermal efficiency. Results show that the extension of the STES outside the canopy zone has a higher temperature rise than the system without the extension. The trendline clearly shows a larger gap between the two cases. When the temperature difference is higher, the higher energy output is produced from the system. Hence, the thermal efficiency would also increase due to its linear relationship with the energy output. The higher reading in temperature rise indicates that the system has a larger heat transfer rate. As the temperature rises, the air density decreases, causing it to rise. Thus, the convection in the system causes an increase in the buoyancy force.

The estimated thermal efficiencies of the system are plotted, as shown in Figure 7, as instantaneous thermal efficiency at each hour. The experimental measurement started at 09:00 am, and the efficiencies were low and gradually increased until 1:00 pm. The efficiencies for both systems started to decline as it reached late afternoon, starting from 3:00 pm. It could also be seen that the efficiency during the late afternoon hours is higher than in the morning. This is because the system has a lower temperature in the morning. As a result, more heat was needed to raise the system's temperature. However, in the evening, the accumulated thermal energy in the collector, which is almost entirely deposited in the black pebbles, works to maintain a higher air temperature than in the morning.

Results show that the extension of the STES outside the canopy improves the system's thermal efficiency compared to without extension. The mean thermal efficiency enhancement caused by the extended STES is around 33.3%. The mean thermal efficiencies without and with STES extension are 1.78% and 2.67%, respectively. The thermal efficiency peaked at approximately 01:00 pm to 02:00 pm for both conditions. This looks like an immediate proportional to the solar irradiance. The peak solar

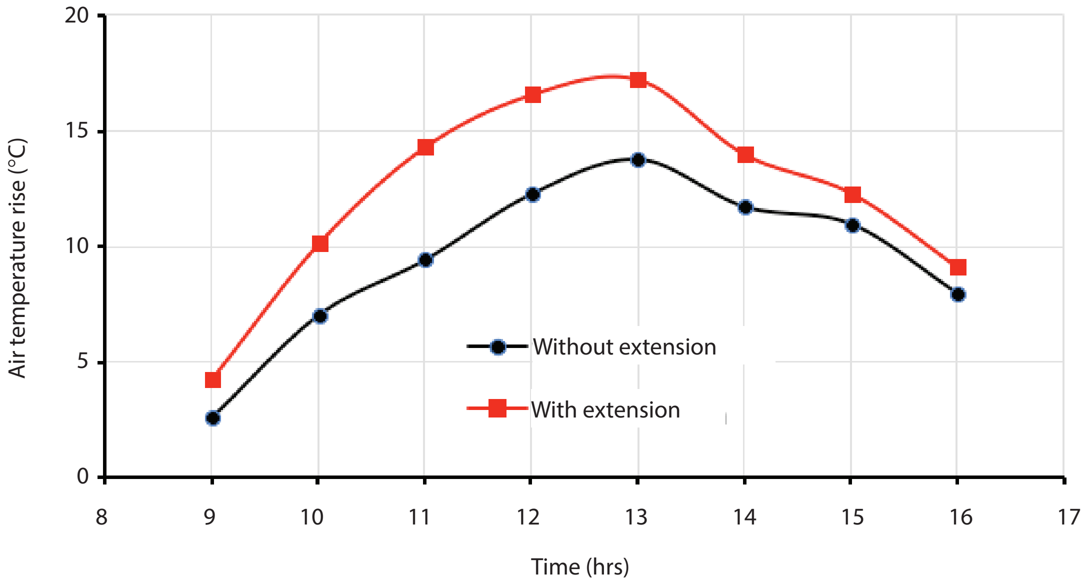

Figure 6 Air temperature trends rise across the SVPG versus time, with and without extended STES

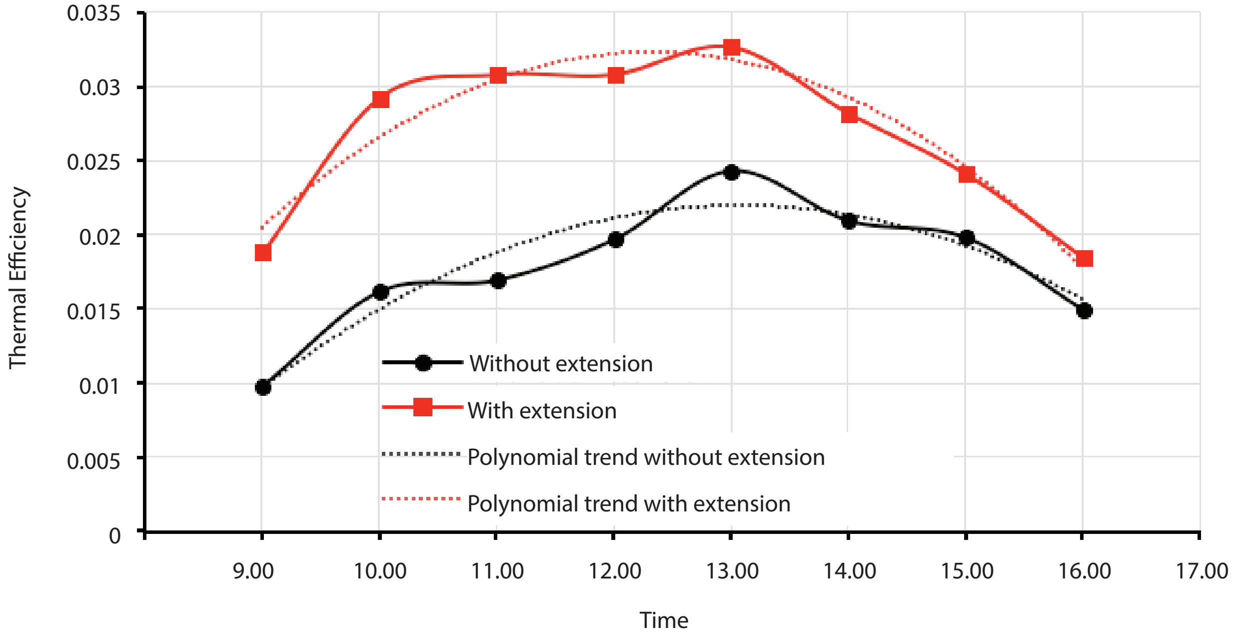

Figure 7 Thermal efficiency variation during the measurement time, without and with STES extension

irradiance and the peak thermal efficiency occur from around 01:00 pm to 02:00 pm. This is similar to the experimental measurement results reported by Al-Kayiem et al. [17]-[18].

Performance Analysis

The key factor that has a major influence on the whole system's performance is the mass flow rate of air. The amount of air mass flow is influenced by the solar irradiance level, properties of the absorber medium and the size of the collector. The current experimental model has a unique feature; the VGE is converted to a secondary absorber for trapping extra solar radiation with high effectiveness. The surfaces of the VGE have been coated with nano black mate paint. This feature permitted the creation of a high-temperature zone that acts as a suction unit, which increased the amount of airflow rate through the system. However, a comparison between the cases without and with extended STES is presented in Figure 8, showing the

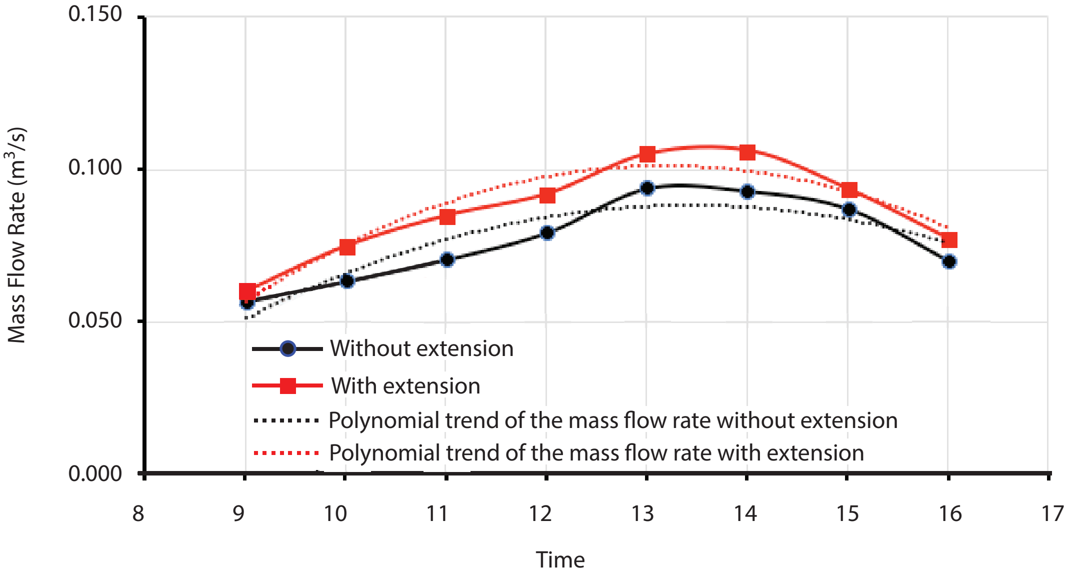

Figure 8 Air mass flow rate variation in the SVPG, with and without extended STES

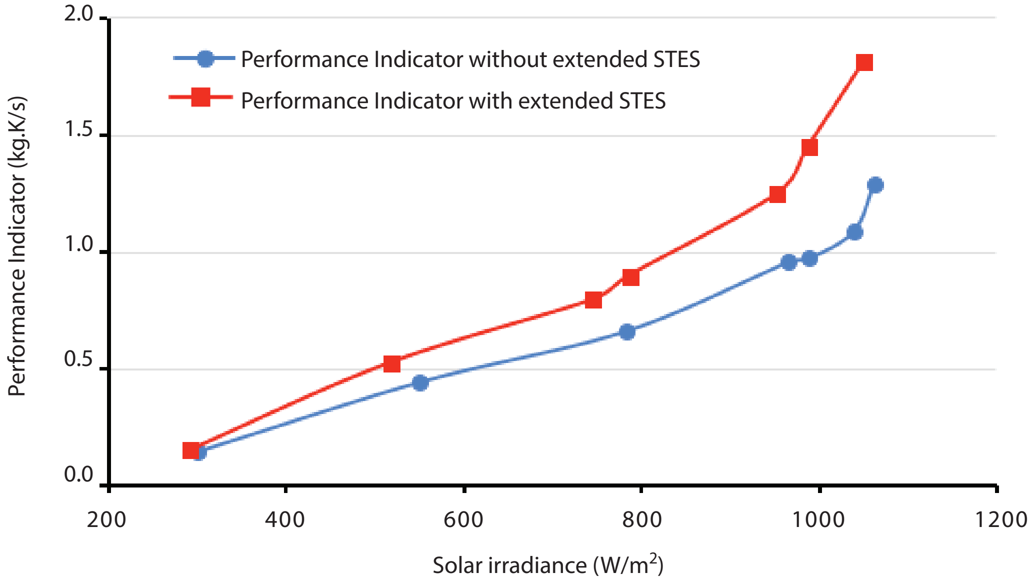

Figure 9 Performance indicator variation versus solar intensity, with and without extended STES

air mass flow rate differences. The trends of both cases are similar, where the mass flow rate increases gradually from morning till the peak at around 1:00 pm to 2:00 pm. The peaks of mass flow rate generated in the system without and with extended STES are 0.0937 and 0.106 kg/s, respectively. The mean air mass flow rate measured for the cases without and with extended STES is 0.077 kg/s and 0.087 kg/s, with a mean increment of 0.01 kg/s achieved due to the extended STES.

To compile all the parameters that have affected the system, a performance parameter has been introduced and evaluated for both cases. The PI results are shown in Figure 9 at various measured solar irradiance. It is clear that solar irradiance is directly influencing the system performance. However, the results for extended STES show higher PI compared to the case without extension. There is no effective system performance enhancement at low solar irradiance of around 200 W/m^2. Once the solar irradiance is higher than 400 W/m^2, the extended STES increases the air particles' temperature before the entrance to the collector. Then, the velocities of the particles become higher, and the amount of the mass flowrate is also higher. The added heat to the airflow before entering the collector increases the temperature rise of the air. The extended STES enhances two parameters; the first is the mass flow rate, and the second is the air temperature rise. As the solar irradiance increases, the PI increases, with noticeable improvement in the case of extended STES. The PI of the tested experimental model reaches 1.0 kg·K/s at around 820 W/m^2 for the case with extended STES, while around 1000 W/m^2 for those without STES. The mean enhancement in the system performance due to the extended STES is around 19.3%.

To summarize, by increasing the area covered by STES while still maintaining the canopy, it is possible to enhance the SUP performance, in general, and the SVPG, in particular. The results in this experimental investigation have proved the selection of extension of pebbles beyond the collector area. Pebbles are easily available, and artificial painting is a low-cost process. Accordingly, the solar updraft efficiency could be enhanced by cheap and easy way through STES and extension outside the collector-covered area. This is a vital finding as this could be a new technique to reduce the cost needed to improve the performance of the overall setup.

CONCLUSIONS

The experimental study of SVPG integrated with TES has been developed, investigated, and evaluated. The conclusion drawn from this experimental investigation is summarized as:

1. It is proven that SVPG integrated with sensible TES can provide better performance.
2. Use of pebbles, which is cheap and easily available, as sensible TES reduces the cost of electricity production by increasing the SVPG performance.
3. An extension of the area covered by black painted pebbles, as extended sensible TES enhances the SVPG performance by around 19.0%.
4. The mean measured thermal efficiency values with the extended STES are higher by around 0.85% than those without extension.

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