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Experimental Studies on Small Scale of Solar Updraft Power Plant

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Abstract – *Solar updraft tower power plant (SUTPP) is an alternative technology for electricity generating from solar energy. It's suitable for use in remote area, where there is high potential of solar radiation, because the constructions are cheap and the technologies involved are conventional. This paper presents the design of a circular and square collector SUTPP to be used in rural areas of developing countries. The design involves heating air using solar energy and the tower effect to raise the hot air up the tower. From this study, a small scale solar updraft tower with 2m length in each side of solar collector, air inlet height of 0.1 m above the ground, an updraft tower of 1.5-meter-high with 2.0 m length of each side collector was studied to determine its performance. Anemometer and multimeter were used to measure the velocity and temperature along the collector and inside the tower. Solar radiation, ambient air temperature as well as air velocity inside the tower were also recorded. These data were taken every one hours in four days to investigate the performance of the SUTPP.*

Keywords: Solar updraft tower power plant, solar energy, solar radiation

1.0 INTRODUCTION

Sensible technology for the wide use of renewable energy must be simple and reliable, accessible to the technologically less developed countries that are sunny and often have limited raw materials resources. It should not need cooling water and it should be based on environmentally sound production from renewable or recyclable materials.

At present, a number of energy sources are utilized on a large scale such as: coil, oil, gas and nuclear. Continuation of the use of fossil fuels is set to face multiple challenges namely: depletion of fossil fuels reserves, global warming and other environmental concerns and continuing fuel price rise. For these reasons, the existing sources of conventional energy may not be adequate to meet the ever increasing energy demands. Consequently, sincere and untiring efforts shall have to be made by the scientists and engineers in exploring the possibilities of harnessing energy from several non-conventional energy sources (solar, biomass, tidal, hydrogen, wind and geothermal energy) which they are seen as possible solution to the growing energy challenges. According to energy experts, unconventional energy sources can be used for electric power generation which receives a great attention [1]. Power generating technology based on green resources would help many countries improve their balance of payments. The solar updraft tower's three essential elements – solar air collector, chimney/tower, and wind turbines - have been familiar for centuries. Their combination to generate electricity has already been described in 1931. Haaf [3,4] provided test results and a theoretical description of the solar tower prototype in Manzanares, Spain. Transferability of the results obtained in Manzanares was discussed by Schlaich et al. [10]. Kreetz [4] introduced the concept of water-filled bags under the collector roof for thermal storage. Gannon and Backström [12] presented a thermodynamic cycle analysis of the solar tower, and also an analysis of turbine characteristics. A thermal and technical analyses targeting computer-aided calculation was described by dos Santos Bernardes et al. [16].

The basic physical principles of centralized electricity generation with solar chimney power plants (SCPP's) were described by Haaf et al. [2,3] in 1982. After the pilot plant in Manzanares had gone into operation in June 1982, the first experimental results confirmed the main assumptions of the original physical model [2,4]. Later, on the basis of experimental data from July 1983 to January 1984, a semi-empirical, parametrical model was proposed for predicting the monthly mean electrical power output of the pilot plant as a function of solar irradiation [5]. The model predictions agreed reasonably with the experimental data for the exceptionally dry months July- October 1983, but the model failed to simulate the wet months following heavy rainfall in winter and spring 1984. It was realized, that natural precipitation entering the collector has a fundamental influence on the collector performance via evaporation, plant growth and infrared absorption in the collector air [2] a refined parametrical model was therefore proposed, which includes at least the long term, seasonally varying effect on rainwater on the plants performance and allows the simulation of large plants in climates similar to the climate in Manzanares [6]. The cost of electricity generation was estimated in [2,6] and calculated in details in [6].

2.0 WORKING PRINCIPLE

As presented in the Fig.1, a Solar Updraft Tower converts solar radiation into electricity by combining three well-known principles: the greenhouse effect, the tower and wind turbines in a novel way. Hot air is produced by the sun under a large glass roof [8]. Direct and diffuse solar radiation strikes the glass roof, where specific fractions of the energy are reflected, absorbed and transmitted. The quantities of these fractions depend on the solar incidence angle and optical characteristics of the glass, such as the refractive index, thickness and extinction coefficient. The transmitted solar radiation strikes the ground surface; a part of the energy is absorbed while another part is reflected back to the roof, where it is gain reflected to the ground. The multiple reflection of radiation continues, resulting in a higher fraction of energy absorbed by the ground, known as the transmittance-absorptance product of the ground. Through the mechanism of natural convection, the warm ground surface heats the adjacent air, causing it to rise. The buoyant air rises up into the chimney of the plant, thereby drawing in more air at the collector perimeter and thus initiating forced convection which heats the collector air more rapidly. Through mixed convection, the warm collector air heats the underside of the collector roof. Some of the energy absorbed by the ground surface is conducted to the cooler earth below, while radiation exchange also takes place between the warm ground surface and the cooler collector roof. In turn, via natural and forced convection, the collector roof transfers energy from its surface to the ambient air adjacent to it [7]. As the air flows from the collector perimeter towards the chimney its temperature increases while the velocity of the air stays approximately constant because of the increasing collector height. The heated air travels up the chimney, where it cools through the chimney walls. The chimney converts heat into kinetic energy. The pressure difference between the chimney base and ambient pressure at the outlet can be estimated from the density difference. This in turn depends upon the temperatures of the air at the inlet and at the top of the chimney. The pressure difference available to drive the turbine can be reduced by the friction loss in the

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chimney, the losses at the entrance and the exit kinetic energy loss [8]. As the collector air flows across the turbine(s), the kinetic energy of the air turns the turbine blades which in turn drive the generator(s) [7].

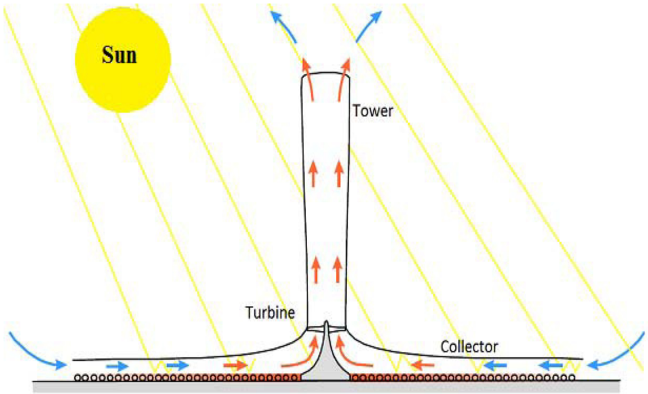

Figure 1: Solar Updraft Tower Power Plant description

3.0 MAIN COMPONENTS OF A SOLAR COLLECTOR

A. The Collector. The major component of a solar chimney power station is the solar collector. Solar energy collectors are special kind of heat exchangers that transform solar radiation energy to internal energy of the transport medium [9]. The collector is the part of the chimney that produces hot air by the greenhouse effect. It has a roof made up of plastic film or glass plastic film. The roof material is stretched horizontally two or six meter above the ground (Fig.2). The height of the roof increases adjacent to the chimney base, so that the air is diverted to the chimney base with minimum friction loss. This covering admits the short wave solar radiation component and retains long-wave radiation from the heated ground. Thus the ground under the roof heats up and transfers its heat to the air flowing radially above it from the outside to the chimney. The structure of the collector changes to the covering material we used.

Significant research effort has been put into the construction, simulation and operation of the solar chimney collector. Two types of collectors were tested by Pasumarthi and Sherif [5]: (1) extending the collector base and (2) introducing an intermediate absorber. The experimental temperatures reported are higher than the theoretically predicted temperatures. The authors explain that one of the reasons for this behavior is the fact that the experimental temperatures reported are the maximum temperatures attained inside the chimney, whereas the theoretical model predicts the bulk air temperature [11]. An analytical model has been presented by Schlaich [10]. Early numerical models have been presented by Kröger and Buys [12]. Kröger and Buys [12] presented a detailed plant analysis also with a transient collector to predict the maximum powers for a one-year operational cycle [20]. In Lombaard et al [13] investigation, the temperatures of the insulated collector plate and glass cover of an horizontal solar collector were measured and compared to theoretically predicted values for different ambient conditions. By ernploying an appropriate equation for the prediction of the heat transfer between the cover and the natural environment, good agreement was obtained between the theoretically predicted and experimentally measured values. Hamdan [14] presented an analytical model to predict the performance of a solar chimney power plant. The turbine head has a very strong effect on the second-law efficiency and total harvested power [14]. In 2005, Canadian E. Bilgen and J. Rheault [15] proposed the construction of the solar collector in a

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sloppy and tapered (with high altitude) section. This idea is of course a brilliant and new idea because the angle of inclination would aid in providing sufficient and effective area of the collector to receive solar radiation, thereby improving the solar collector efficiency. And improving solar collector efficiency would increase the amount of useful heat needed to warm up the cold air.

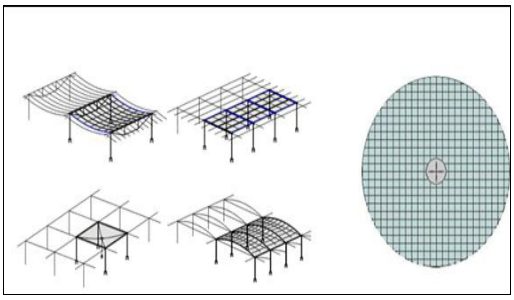

Figure 2: Collector design options

B. Tower/Chimney. The function of chimney is to convert the thermal energy produced in the collector into a kinetic energy; it is determined by both the temperature rise of the ambient airflow from the collector inlet to the collector outlet and the height of the chimney. The pressure difference is produced due to the density difference between the airflow at chimney base.

There are various different methods for constructing such a tower: free-standing reinforced concrete tubes, steel sheet tubes supported by guy wires, or cable-net construction with a cladding of sheet metal or membranes (Fig 3) [16]. The design procedures for such structures are all well established and have already been utilized for cooling towers; thus, no new developments are required. Detailed static and structural-mechanical investigations have shown that it is expedient to stiffen the tower in several stages, so that a relatively thin wall material will suffice. Our solution is to use bundles of strands in the form of ―flat―spoked wheels which span the cross-sectional area of the tower. This is perhaps the only real structural novelty in these towers as compared to existing structures. Schlaich [5,17,18] suggested the reinforced concrete as a building material structure towers high. Studies have shown that practically this method of construction is the alternative most sustainable and cost-effective. Such towers can also be constructed using other technologies including: guyed steel towers which frame is covered with nets of steel cables, membranes or trapezoidal metal films. The maximum height for solar chimney is 1000 m. To support high chimney structure and gigantic solar, compression ring stiffeners are installed with a vertical spacing [19].

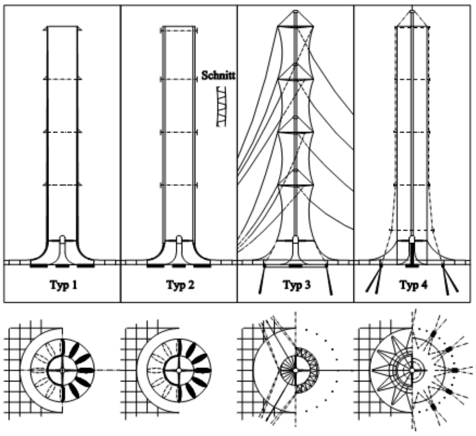

Figure 3: Chimney construction shapes [35].

C. Turbines. Turbines are always placed at the base of the chimney. Using turbines, mechanical output in the form of rotational energy can be derived from the air current in the chimney. Turbines in a solar chimney do not work with staged velocity as a free running wind energy converter, but as a cased pressure-staged wind turbo generator, in which similar to a hydroelectric power station, static pressure is converted to rotational energy using a cased turbine.

By using turbines, mechanical output in the form of rotational energy can be derived from the air current in the tower. Turbines in a solar updraft tower do not work with staged velocity like free running wind energy converters, but as shrouded pressure-staged wind turbo generators, in which, similarly to a hydroelectric power station, static pressure is converted to rotational energy using cased turbines. Air speed before and after the turbine is about the same. The output achieved is proportional to the product of the volume flow per time unit and the pressure differential over the turbine. With a view to maximum energy yield, the aim of the turbine control system is to maximize this product under all operating conditions. To this end, the blade pitch is adjusted during operation to regulate the power output according to the changing airspeed and airflow. If the flat sides of the blades are perpendicular to the airflow, the turbine does not turn. If the blades are parallel to the air flow and allow the air to flow through undisturbed, there is no pressure drop at the turbine, and no electricity is generated. Between these two extremes there is an optimum blade setting: the output is maximized if the pressure drop at the turbine is about 80% of the total pressure differential available. The optimum fraction depends on the plant's characteristics such as friction pressure losses.

D. Energy storage in the collector. The ground under the collector roof behaves as a storage medium, and can even heat up the air for a significant time after sunset. The efficiency of the solar chimney power plant is below 2% and depends mainly on the height of the tower. As a result, these power plants can only be constructed on land that is very cheap or free. Such areas are usually situated in desert regions. However, this approach is not without other uses, as the outer area under the collector roof can also be utilized as a greenhouse for agricultural purposes [21]. Water filled black tubes are laid down side by side on the black sheeted or sprayed soil under the glass roof collector (Fig.4). They are filled with water once and remain closed thereafter, so that no evaporation can take place. The volume of water in the tubes is selected to correspond to a water layer with a depth of 5 to 20 cm depending on the desired power output. Since the heat transfer between black tubes and water is much larger than that between the black sheet and the soil, even at low water flow speed in the tubes, and since the heat capacity of water (4.2 kJ/kg) is much higher than that of soil (0.75 - 0.85 kJ/kg) the

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water inside the tubes stores a part of the solar heat and releases it during the night, when the air in the collector cools down [20].

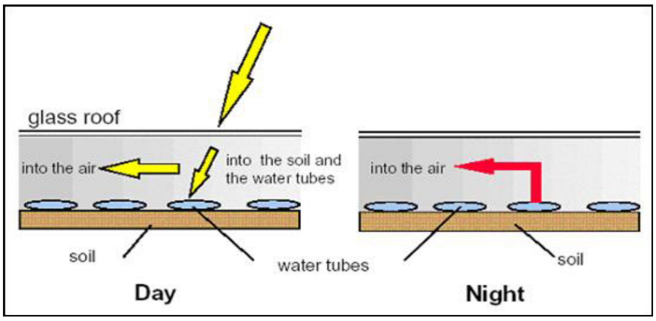

Figure 4: Principle of heat storage underneath the roof using water-filled black tubes [55].

4.0 GENERAL SYSTEM CHARACTERISTICS

Apart from working on a very simple principle, solar updraft towers have a number of special features:

1. Unlike conventional power stations (and also some other solar thermal power station types), solar updraft towers do not need cooling water. This is a key advantage in the many sunny countries that already have major problems with their water supply.

2. The collector can use all types of solar radiation, both direct and diffuse. This is crucial for tropical countries where the sky is frequently overcast.

3. Due to the soil under the collector working as a natural heat storage system, solar updraft towers can operate 24 h a day on pure solar energy and at reduced output during the night time. If desired, additional water tubes or bags placed under the collector roof absorb part of the radiated energy during the day and release it into the collector at night. Thus solar updraft towers can operate as base load power plants. As the plant's prime mover is the air temperature difference (causing an air density difference) between the air in the tower and ambient air, lower ambient temperatures at night help to keep the output at an almost constant level even when the temperature of the natural and additional thermal storage also decreases without sunshine, as the temperature difference remains practically the same.

5.0 EXPERIMENTAL SETUP

A. Protoype setup. A pilot experimental prototype for the SUTPP was erected in open area at Mechanical Engineering Campus at UTM Kuala Lumpur which consists of a 2m x2m collector and 1.5m tall tower for square collector and 2m diameter with 1.5m tall tower for circular collector. A pvc pipe with diameter of 80mm and height of 1.5m is used to construct the solar tower which is supported by flat bar. The collector is constructed using flat bar (for circular collector) and pvc pipe (for square collector) with transparent plastic cover as shown in Fig. 5(a) and 5(b). The collector surface is designed with no inclination with collector height from the ground of 1.0m.

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(a)


(b)

Figure 5: (a) Circular Collector. (b) Square Collector.

B. Technical data of the prototype. The different shapes of the prototype plan as designed are given in Table I and Table II.

Table 1: Technical data of the design of circular collector.

Tower Height	1.5 m
Tower Diameter	80 mm
Collector Diameter	2 m
Collector Slope Angle	0°
Tower Material	PVC
Collector Material	Flat Bar
Collector Shape	Circular

Table 2: Technical data of the design of square collector.

Tower Height	1.5 m
Tower Diameter	80 mm
Collector Diameter	2 m
Collector Slope Angle	0°
Tower Material	PVC
Collector Material	PVC Pipe
Collector Shape	Square

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C. Experimental procedure. In order to obtain comprehensive data on the performance of the solar updraft tower, data were collected under two different design (circular and square collector). The air velocity was measured and recorded under the following constraints (1) When the circular collector was installed. (2) When the square collector was installed.

Prior to each test condition, two equipment was used to measure the value of air flow and temperature so that all the relevant data could be recorded. Also when all the initial tests were done, automatic measurements of air flow and temperatures were initiated. During the operation of the solar updraft tower power plant, we measured the following parameters. The data were recorded every one hour starting 12.00 pm until 4.00 pm for 4 days; (1) Temperature (˚C) (2) Air Flow (m/s)

D. Mathematical model. The output power of the plant depends upon various parameters presented simply by the following equation. The tower (chimney) converts the heat-flow produced by the collector into kinetic energy (convection current) and potential energy (pressure drop at the turbine). Thus the density difference of the air caused by the temperature rise in the collector works as driving force. The lighter column of air in the tower is connected with the surrounding atmosphere at the base (inside the collector) and at the top of the tower, and thus acquires lift. A pressure difference is measured between tower base (collector outlet) and the ambient [22].

6.0 RESULT AND DISCUSSION

Figure shows the graph for both shape of collector which circular collector and square collector data points plotted respect to the time at 12pm until 4pm for 4 days.

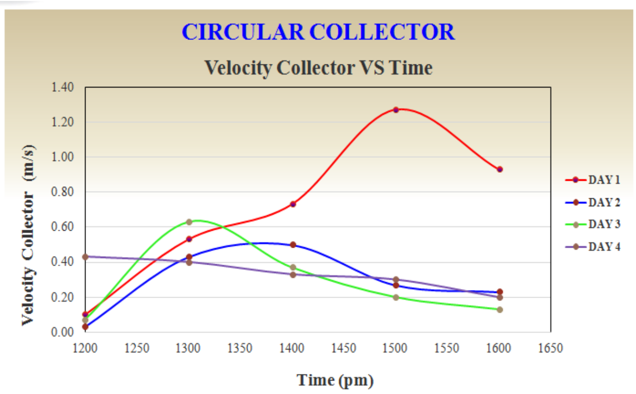

Figure 6: Air velocity under a circular collector.

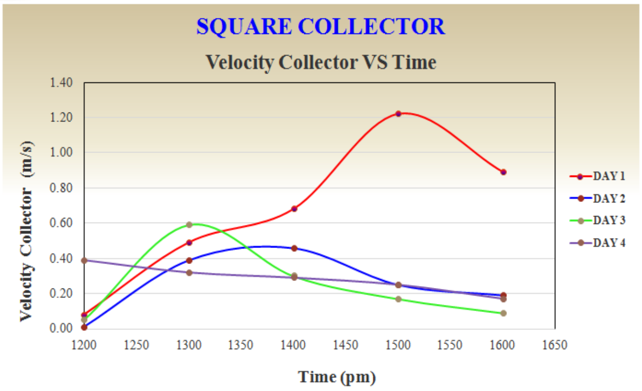

Figure 7: Air velocity under a square collector.

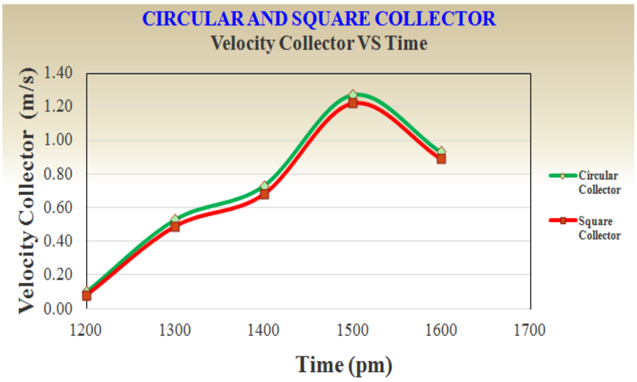

Figure 8: Comparison of the highest air velocity under square and circular collectors.

From the data collected, Fig.7 shows the velocity air flow for circular collector and Fig.8 shows the velocity air flow for square collector. It appears that the velocity at circular is morehigher than square collector. As shown, the velocity increased from 12pm until 3pm and decreased at 4pm and maximum velocity occur at 3pm for both shapes. The velocity decreased from 1.27 m/s to 0.93 m/s for circular shape and from 1.22 m/s to 0.89 m/s at 4pm. Value of maximum velocity for circular collector is 1.27 m/s and 1.22 m/s for square collector. As a result, the velocity inside collector and outside tower affected with this two shape of collector.

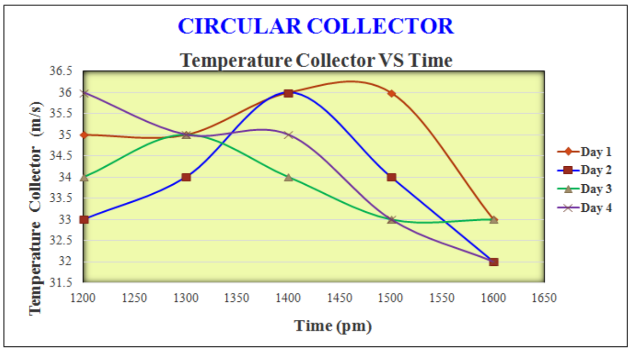

Figure 9: Temperature values for circular collector.

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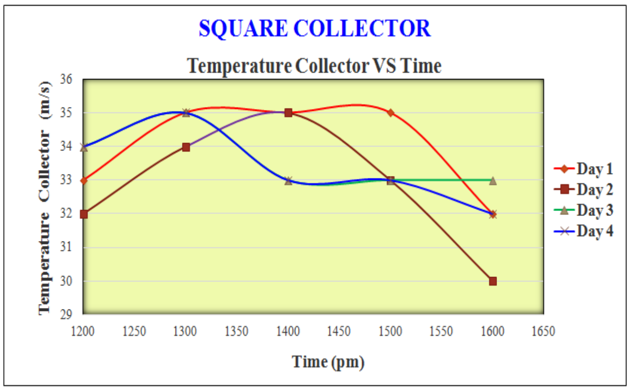

Figure 10: Temperature values for square collector.

The temperature under the collector is presented in figure 5.20. The data for every one-hour start from 12.00 pm to 4.00 pm in one day are presented. The peak of maximum temperature for the collector is around 3.00 pm. This experiment was carried out at the same time for circular shape and square shape. It appears that temperature at circular shape is higher than the square shape. As shown, the maximum temperature occurs at 3pm for both shapes. The temperature inside the tower is depending the temperature absorbed in the collector. Due to greenhouse effect the temperature inside the tower is higher than the temperature at surrounding.

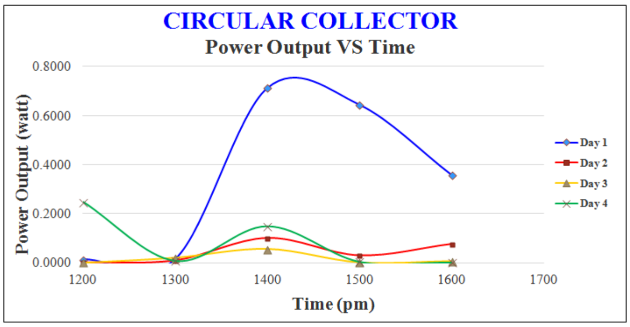

Figure 11: Calculated power output for circular collector.

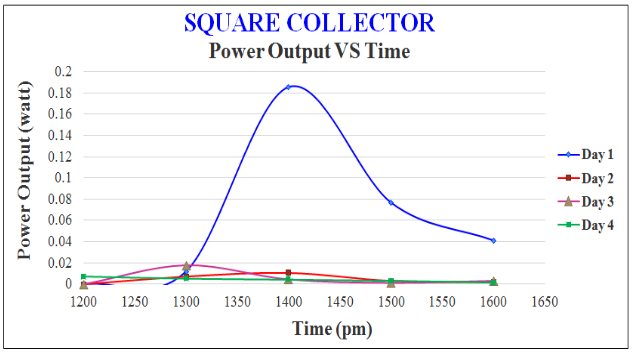

Figure 12: Calculated power output for square collector.

The highest value power output for both shape on 1400 hours which 0.7129 W for circular shape and 0.1855W for square shape. Large quantities of warm air have to be lifted from the ground to chimney top which results in gravitational energy loss. The air that leaves the chimney is above ambient temperature at that altitude also resulting in thermal energy loss.

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As ambient air is drawn into the collector and warmed, expands with little increase in pressure and the majority of solar input is lost in the simple expansion of air before it reaches the turbine. The circular collector solar chimney gives more output power than square shape because it gives more heat transfer surface than the square. There are a number of reasons as to why a large area of include the fact that the overall conversion efficiency from temperature drop with altitude of about 10 lifted from the ground to chimney top which results in gravitational is above ambient temperature at that altitude also resulting in thermal the collector and warmed, expands with little increase in pressure and simple expansion of air before it reaches the turbine. The following are concluded from the experimental data:

1. The model of Solar Updraft Tower with different shape of collector successfully constructed at UTM Kuala Lumpur.
2. The circular collector gives higher velocity output than the square collector solar updraft tower due to the circular collector gives more heat transfer surface than the square collector.
3. The maximum peak velocity in collector occurs at peak temperature.
4. The collector’s outlet temperature is a function of the collector’s area and the solar radiation; it increases as the collector’s diameter and solar radiation increasing.

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