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INVESTIGATION ON THE INFLUNCE OF COLLECTOR HEIGHT ON THE PERFORMANCE OF SOLAR CHIMNEY POWER PLANT

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ABSTRACT

The solar chimney power plant (SCPP) has the potential of converting solar energy indirectly to electrical energy using a combination of greenhouse technology, chimney technology, wind turbine and a generator. The present paper presents results of investigation on the performance of a prototype SCPP at different canopy height at constant chimney diameter and height of 0.32 m and 6.3 m, respectively. The investigation was conducted experimentally using an experimental model designed, fabricated, and subjected to measurements under Malaysia weather conditions. The experimental SCPP model has a collector diameter of 3 m and the absorbing medium was black painted pebbles while the transparent canopy was made of Perspex. The investigations were carried out for different canopy heights, above the absorber at the inlet section, of 0.05, 0.1, 0.15 and 0.2 m. The selected performance parameters for comparison were the air stream temperature in the collector, the mass flow rate created in the system measured at the chimney base, and the system efficiency during the day. The results have shown that the lowest canopy height, 0.05 m performed better than the other tested heights. It is recommended to extend the investigation by studying the system performance under various collector diameters.

Keywords: solar chimney, canopy height, solar system performance.

INTRODUCTION

The solar collector is one of the devices which can absorb and convert energy form the sun to a usable or storable energy in many applications such as drying the agricultural products, marine products as well as heating of the building. There are varieties of designs for solar thermal collector application, like parabolic trough, solar air collector (flat plate collector) widely used in the SCPP. When solar radiation reaches the surface of the transparent cover of a solar collector (canopy) some of the radiation is reflected back while high percentage of the radiation pass through the Perspex to the ground (black pebbles) that absorbed and converts the solar energy to thermal energy in the collector. The collector of a SCPP has been majorly considered as one component of the system that can be improved to enhance the performance of a SCPP. Al-Azawie *et al.* [1] considered different types of ground materials and presented the preliminary results of an experimental and numerical study on enhancing SCPP collector performance. They discussed and compared the results of the ground materials and concluded that the ceramic and the stone performed better than the other types of materials.

Shyia [2], conducted experimental and numerical investigations on SCPP model developed in Baghdad which has 6 m chimney height, 6 m collector diameter with variable canopy heights of 0.1, 0.15 and 0.2 m. The results analysis showed that at 2:00 pm, the air velocity at the chimney base was 3.12 m/s and the air temperature was 52.5°C, respectively for 0.1 m canopy height which was found to give best performance. Schaich *et al* [3] investigated the design of a 100 MW power plant which had 1000 m tall chimney with a 110 m diameter and a 200 MW power plant which had a 1000 m tall chimney with a 120 m diameter.

Zhou, *et al* [4] carried out theoretical analysis on the effect of the chimney height on the performance of the SCPP. The theoretical investigation was based on the data of Manzanares solar chimney prototype. The results show that as standard lapse rate of atmospheric temperature is used, the maximum power output of 102.2 kW is obtained for the optimal chimney height of 615 m, which is lower than the maximum chimney height with a power output of 92.3 kW. They concluded that with respect to a special collector, negative buoyancy at the latter chimney will occur if chimney height is more than the maximum height. The power plant would obtain the maximum energy conversion efficiency if chimney height is equal to the optimal height. Al-Kayiem [5] investigated the performance of solar chimney power plant experimental, analytically and numerically for a model with collector diameter of the collector was 2.1 m and absorbing medium of black painted pebbles while the canopy was made of Perspex. The model has variables chimney and canopy height. The analytical results were validated with the experimental data. The performance indicators selected for the validation and comparison were collector buoyant air temperature and air mass flow rate generated in the system. The results showed that the lowest canopy height performed better than the higher ones and the system performed betters as the chimney height increased.

To optimized collector performance, the flow rate of incoming air to the collector should be commensurate with the energy transfer from the absorber, thus the canopy height controls the inflow air to the collector while the collector size influences the energy gained in the collector.

The present work investigates the influence of various canopy heights with constant geometrical parameters such as fixed chimney height, diameter and

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fixed collector diameter to improve the performance of SCPP. Geometric parameters such as collector inlet opening and collector outlet height were varied and tested with different configurations to study and improve the air flow characteristics inside a SCPP.

EXPERIMENTAL IMPLEMENTATIONS

The experimental model was constructed in the present work with unique feature of variable canopy heights with constant chimney heights. The solar chimney model was subjected to series of experimental investigations and measurements.

COLLECTOR COMPONENT

The collector component of the experimental model has the absorber material of dull black painted rocks (pebbles) to increase solar radiation absorptivity. According to Incropera *et al,* (2007) [6], such type of ground has absorptivity of 0.9 and emissivity of 0.95. Over the black painted rocks, is transparent cover (canopy) made of Perspex and supported with metal bars designed such that the height above the rocks can be varied through the adjustable frames. The canopy is also designed to slop at 15° from the periphery to the centre where it is connected to the chimney. The 15° slope was necessary to enhance and channel buoyant air stream to the chimney and avoid the abruptness of air convergence. The slope also promotes self-cleaning of the cover and enhances transmissivity of the Perspex. The canopy adjustable frame is designed in such a way that it can be raised with a light pull in the upwards/downwards direction. In the adjustable frame of the canopy structure, are pre-drilled holes for the stopper hooks to maintain any specific height at any experimental variable height. The design provides four different heights of the canopy above the absorber surface considered at The model was created to investigate the optimum height at which the available energy gained by the collector will yield highest efficiency and improve energy storage for night and cloudy weather operations.

CHIMNEY

The chimney is the pressure tube and was made of PVC pipe and installed at the centre of collector. The chimney used for this experiment has 0.32 m diameter and 6.3 m length/height which is joined to the top of the canopy. The fabricated solar chimney power plant model was employed for experiments in an open area where there is no obstruction to the air flow and solar radiation. A solid base made out of multiple blocks and solid materials provides reasonably good support to the whole model.

MEASURING INSTRUMENTS

For better results, it is required to measure the ground, canopy and the air inside the collector temperature all in the south location. However, for average reading and precise determination of temperature distribution in the system, the thermocouples were distributed over the surfaces of the collector components. Three Type K surface thermocouples were evenly distributed on the canopy surface to capture the surface temperature. At the absorber surface (the black painted pebbles), another three type K surface thermocouples where installed to measure the absorber temperatures. The air temperature in the greenhouse was measured using their type K probe thermocouples distributed within the greenhouse. The thermocouples distributions were done such that temperatures at different points in the system were captured from the inlet to the centre of the collector. In the chimney there are three type K probe thermocouples installed along the chimney height and distributed as shown in **Error! Reference source not found.**1. The thermocouple wires were connected to a digital data logger, GRAFTECH midi logger LG800 with 20 channel inputs. Air flow velocity was measured with vane-probe and hotwire-probe sensors connected to digital anemometer model TPI 575C1. By using the portable hot wire anemometer, which has extendable length, one could capture the air velocity at the centre of the canopy as well as the chimney inlet velocity and measuring the pressure at in let of the chimney. The total solar intensity in south location was measured using digital solar meter, that was fixed at ambient and another one fixed under the canopy on the pebbles surface.

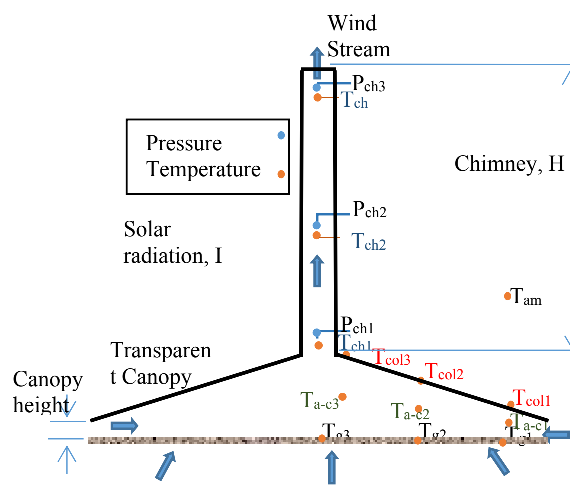

Figure-1. Schematics of solar chimney with main components and shows the experimental setup.

PERFORMANCE EVALUATION PROCEDURE

The experimental measurements were conducted outdoor at varied canopy heights 0.05, 0.01, 0.15 and 0.2 m. Each investigation with respect to any canopy height was conducted for four days. The temperature measurements for the various surfaces and components were recorded and evaluated on average. The average temperatures for the ground, canopy, system air temperature and the ambient temperatures are represented with T_g, T_c, T_{air} and T_a respectively. Summary of the experimental cases is shown in Table-1.

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Table-1. The experimental measurement cases.

Canopy height (m)	Time of measure	Repeatability (days)
0.05	8:00am,10:00am,12:00pm, 2:00pm,4:00pm, 6:00pm and 8:00pm	4 days
0.01		4 days
0.15		4 days
0.20		4 days

To determine some thermo physical properties of air and evaluate the performance of the system, some empirical equations were employed. The properties of air at the temperature range of 300 and 350 K following empirical relationship were used to determine the air density and specific heat at various temperatures using Equation 1 and 2 respectively.

$$\rho = 1.1614 - 0.00353 * (T - 300) \quad (1)$$

$$C_p = (1.007 + 0.00004(T - 300))1000 \quad (2)$$

The energy useful energy gained by the air in the collector is determined using Equation 3.

$$Q_u = \dot{m} c_p \Delta T \quad (3)$$

Energy supplied to the collector of the system from solar radiation is presented using Equation 4:

$$Q_{in} = I \cdot A_{collector} \quad (4)$$

Energy conversion efficiency in the collector component, chimney and the system considering no-load condition is as shown in Equations 5, 6 and 7 respectively:

$$\eta_{collector} = \frac{\dot{m} c_p \Delta T}{I \cdot A_{collector}} \quad (5)$$

$$\eta_{ch} = \frac{g.h}{c_p.T_{ch}} \quad (6)$$

$$\eta_{system} = \eta_{col} . \eta_{ch} \quad (7)$$

The above basic mathematical equations were converted to a computer program to solve for the performance at various canopy heights and time of the day.

RESULTS AND DISCUSSIONS

Following the various canopy heights considered in this investigation, **Error! Reference source not found.**2, represents the average hourly energy transport parameter (ṁΔT) at various canopy heights for different times of the day (8:00 am - 8:00 pm). From sunrise till solar noon, it was observed that ṁΔT is continually increasing with the time but decreases as the solar radiation intensity drops after solar noon till sunset.

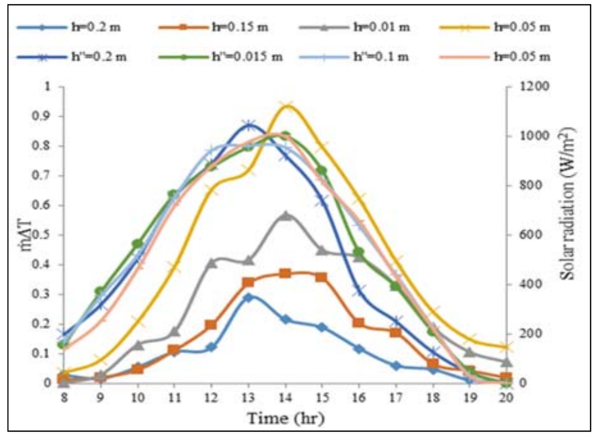

Figure-2. Influence of ṁΔT and the solar radiation vs. time at variable canopy height.

The maximum ṁΔT was observed at the canopy height of 0.05 m with a value of 0.933148 kg. K/s at 1:00 o'clock when the solar radiation was maximum and equal to 997.75 W/m². It was also noticed that the minimum ṁΔT was at the canopy height of 0.2 m with a value of 0.289 kg. K/s when the solar radiation was maximum at 1:00 pm is 1042.7 W/m².

In **Error! Reference source not found.**3, it is obvious that at canopy height of 0.05 m, the collector performance and system efficiency are of the highest values as compared to results for canopy height 0.1 m, 0.15 m and 0.2 m which is similar to experimental observations reported by Shiya (2002) [2]. The experimental results are reasonable and acceptable based on logic of inertia forces. Noticeably from this figure the efficiency of the system when the canopy height equal 0.2 m are smallest value compared with rest their values for different canopy heights.

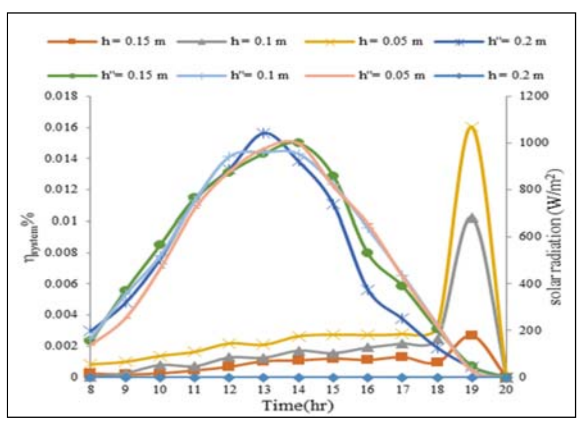

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Figure-3. The influence of efficiency and the solar radiation against the time.

In the **Error! Reference source not found.**4, a representation of the temperature of the ground behaviour in the day from morning until the night is presented. The result shows the influence of the variation of canopy heights on the temperature of the ground in whole system with respect to times starting form (8:00 am- 8:00 pm). At the canopy height is 0.05 m the temperature of the ground was maximum compared to the ground temperatures at other canopy heights at same time of the day. The average temperature increment (between the collector ground and ambient) was around 41.41 $\overset{o}{C}$ with 0.05 m height at 2:00 pm. While for the canopy height of 0.2 m the temperatures were lowest even though the solar radiation intensity was high on the days of the experimentations. The average temperature increment (ground and ambient) is around 25.23 $\overset{o}{C}$ with 0.2 m height at 3:00 pm and shows low buoyancy driven flow. This infers that the volume of air has influence on the heat removal factor on the collector absorber and buoyancy in the system because of the dependence on density difference.

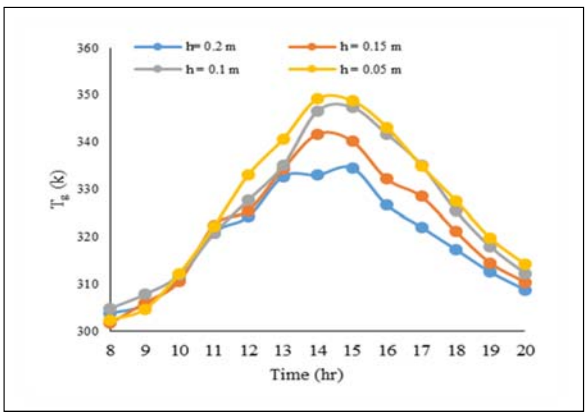

Figure-4. Temperature of the ground at different times of the day for various canopy heights.

The higher temperature recorded by the ground when the canopy height was 0.05 m was as a result of low air inflow to the system thereby providing optimum heat transfer to the available air and increase buoyancy. On the other hand, when the air inflow increases, the heat removal factor increases leading to reduced temperature of the ground. As the canopy height continues to increase, the air volume will exceed the capacity where the ground temperature may be able to initiate buoyancy in the air; consequently, the internal energy of the air becomes lower thus leading to stagnation and increased residence time of the air in the collector.

In **Error! Reference source not found.**5, the available air power generated at the chimney with different canopy height is presented. It was observed from the figure that the available power was higher in the case when the canopy height was lowest at 0.05 m.

In the solar chimney itself, regardless of the heat transfer mechanism, there are two natural forces involved: buoyancy force and inertia force. Buoyancy force is one that is responsible for the updraft of air due to difference in density and pressure difference along the chimney. Whereas inertia force is involved when the surrounding is cooler wind blew pass and forces the hotter and lighter air out from below the canopy of the solar chimney resulting in cooler air to occupy the spaces in between the canopy cover and ground collector.

Based on the 2nd law of thermodynamics, heat transfer always occurs from a higher temperature entity to a lower temperature entity. Thus, when cooler air occupied the spaces in between the canopy and ground after replacing the hotter and lighter air trapped inside, the ground collector initially heated to a higher temperature will be transferring heat with the cooler air, thereby, lowering the system performance and its efficiency. This would be a common phenomenon when the canopy height is high.

Because there will be less obstacles for the surrounding wind to blow pass.

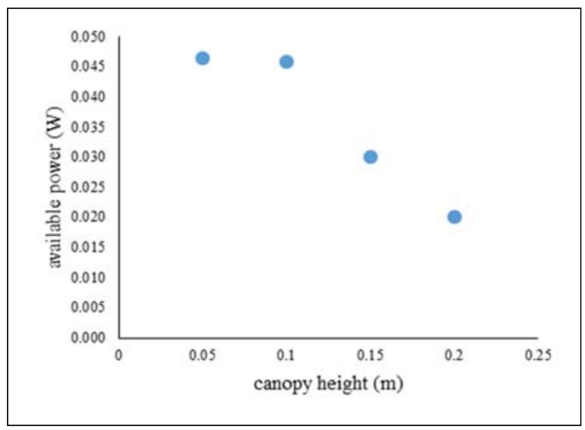

Figure-5. Power available for different canopy height.

Nomenclature

A	Area [m^2]
C_p	Specific heat [kJ/kg. K]
g	Gravitational acceleration [m/s^2]
h	Chimney height [m]
I	Solar radiation [W/m^2]
$\dot{m}$	Mass flow rate [kg/s]
Q_u	Useful energy [kJ/s]
ΔT	Temperatures difference [K]
T_{ch}	Temperature of chimney [K]
Greek Symbol	
$\eta_{collector}$	Collector efficiency
$\eta_{chimney}$	Chimney efficiency
η_{system}	System efficiency
.ρ	Density [kg/m^3]

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CONCLUSIONS

This article investigates the performance of the solar chimney project by using a model that was designed, locally fabricated, and subjected to outdoor experimental measurements.

1. By using different inlet canopy height 0.05, 0.1, 0.15 and 0.2 m, the best system efficiency of the solar chimney model is achieved when the canopy height is of 0.05 m.
2. The heat leads for a large temperature gradient near the inlet, and then temperature gradually increase toward to the center of solar chimney.
3. The product of $\dot{m}\Delta T$ as performance indicator is the main parameter that depicts the performance of the collector. The highest $\dot{m}\Delta T$ is achieved at around 1.00 pm to 2.00 pm, where the measured solar irradiation is around 997.75 w/m^2.

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