Experimental Characterization of the Absorptivity of Various Ground Materials for Solar Chimney Application

by

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CERTIFICATION OF APPROVAL

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A project dissertation submitted to the
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Approved by,

____

(A.P. Dr Hussain Hammud Ja'afer Al Kayiem)

UNIVERSITI TEKNOLOGI PETRONAS,
TRONOH, PERAK,
September 2013

CERTIFICATION OF ORIGINALITY

This is to certify that I am responsible for the work submitted in this project, that the original work is of my own except specified in the references and acknowledgements, and that the original work contained herein have not been undertaken or done by unspecified sources or persons.

MOHAMMAD FARHAN BIN ZAMMERI

ABSTRACT

The solar chimney experiment focusing on the type of ground materials which affecting its performance is done because of the influence of the material capability in efficiently absorbs the solar radiation reaching the earth and converting it into thermal energy that is used to heat up the working fluid which is the air. The heated working fluid will flow due to natural convection of different density fluid; hotter air becomes less dense than colder air. The kinetic energy of the working fluid is then enhanced by means of chimney creating pressure difference between the inside of the chimney to the ambient pressure that drive the air flow from the inlet of the solar collector and exits through the chimney outlet. The kinetic energy possess by the moving fluid is then extracted by means of turbine and generator to generate electricity.

In order to simultaneously evaluate the test materials, custom test rig is built having similar working principle to a real life solar chimney power plant. The rig was design to be similar to one another apart to the ground material used in the collector's compartments which are painted ceramics, painted pebbles, sand, painted stones, sawdust and painted plywood. These materials supposedly having different absorptivity factor will affect the performance of the system.

The performance of these ground materials are evaluated using sets of calculations to determine their performance and efficiency in converting the solar radiation energy into kinetic energy of the moving air. It is found that the recommended materials to be used in solar chimney applications are painted plywood, painted stones and painted ceramics. This is due to their absorptivity characteristic that affect the performance of the system. Saw dust, sand and painted pebbles are not recommended as their performance results are not significant enough to be consider a good ground materials.

Other finding is also encountered during the experiment. Initially a problem faced, has become a component to improving the design of the collector to be able to harness not only the sun's radiations but also the above ground wind, further improving the performance of the system by dividing the collector base into several sectors.

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CHAPTER 1

INTRODUCTION

1.1 Background

The solar energy reaching the earth surface can be harness in two ways, the first one is directly being converted to electrical energy using photovoltaic cells and the other method is to convert the solar radiation into thermal energy using collector or concentrator for heating purposes or as kinetic energy for fluid to drive prime mover (turbine) for electrical generation [1]. Using the later method, we are able to drive the turbine with air as the working fluid without the need of water as similar to conventional power plant. This allows solar chimney power plant to be built in desert area which is currently underutilized. The implementation of this project is of great significance for the development of new energy resources and the commercialization of power generating systems of this type and will help developing countries to promote the rapid development of the solar hot air-flows power generation [2].

Solar chimney works on the second method of harnessing the solar energy and converting them into heat. Solar radiation is captured at the collector or base to heat the ground surface that later heats up the fluid which is air. Heated air having lower density will flow upwards and directed towards the chimney. This different of air density between colder and hotter air creates natural draft of air travelling from the base, upward through the chimney. Turbine is installed to harness the kinetic energy of the passing air than are then converted into electrical energy. This construct is called a solar chimney power plant (SCPP).

SCPPs are unfeasible unless they are established with absorbing area at a scale of hundreds of meters. The common practice is to utilize the ground as absorbing media of the solar energy. The absorptivity is of high importance in the performance of the solar chimney as they are one of the factors determining how much of the solar radiation is utilized in heating the working fluid. Accordingly, it is vital to select a suitable type of ground materials which available potentially in the country. The project is aiming to investigate the most practical type of ground material to suit the solar chimney application in Malaysia.

1.2 Problem Statement

The normal practice in SCPP is to utilize the ground as absorbing and energy conversion medium of the solar energy. The type of ground material is essential factor in the SCPP performance, where the sun's radiation conversion to thermal energy takes place at the ground surface. This has not been investigated using potential ground material in Malaysia.

1.3 Objective

1. To investigate and compare the absorbing characteristics of different types of ground materials those are available in Malaysia for SCPP applications.
2. To simulate the solar energy conversion from radiation to kinetic energy in air flow by commercial software.

1.4 Scope of Study

The scope of this study is on the absorptivity of different types of material that is readily available locally to be used as ground material for solar chimney application in converting solar radiation energy into thermal energy. Different types of ground material are subjected to a similar environment and setup and their absorptivity is measured based on the temperature and velocity of the outlet air at the top of the chimney. By measuring these parameters aside from measuring the solar radiation availability during the experiment, we are able to calculate the performance and efficiency of the solar chimney. Due to time constrain and interest of the experiment, thermal storage effect will not be focused for this particular experiment although typical solar chimney application does consist of thermal storage system. Natural thermal storage characteristic of the tested ground is expected in the data pattern.

This experiment is constrained by time as the minimum time required for data collection only is already 3 days excluding the experiment setup. The weather condition also plays important roles as the experiment is to be conducted in the rainy seasons of the year. Number of days suitable to obtain data is limited. Furthermore, the method of conducting this experiment is new and the design and fabrication of the setup has to be made before the experiment to be conducted [3].

The experimental rig or setup, procedures, and analysis method need to be prepared as none similar to this has been attempted before to be set as references. This task will require significant amount of time from the limited period allocated for this course.

The experiment results will give a significant understanding of the type of ground material most suited and practical for a solar chimney application for industrial use. The experiment also help in cost reduction of comparing the absorptivity property of these ground material as 6 materials can be tested simultaneously in parallel configuration in real world situation. No isolation of the system from the environment is done as to achieve the real world behavior from the system itself.

The significance of this experiment is to better understand the behavior and potential of the available solar ground materials in this country to be use in SCPP. This experimental works will assist in the development of other SCPP related experiment being conducted by the facility, both currently and the future. The results obtained from this session will help improve on the design and performance of SCPP suitable to be use in this country. As ground material is one of the components contributes to the performance of SCPP, effective material usage will equate to a higher SCPP performance and efficiency. With Malaysia having its fair share of solar radiation annually, the involvement in research and development of such system is justified to having a greener energy source for the country.

CHAPTER 2

LITERATURE REVIEW

The Earth receives 174 petawatts (PW) of incoming solar radiation (insolation) at the upper atmosphere [4]. Approximately 30% of it is reflected back to the space while the rest is absorbed by clouds, oceans and land masses. The spectrum of solar light at the Earth's surface is mostly spread across the visible and near-infrared ranges with a small part in the near-ultraviolet [5].

SCPP has been proven capable of generating electrical energy from the Sun. The power plant consists of a chimney paired with a translucent collector at the base which heats the air near the ground and guides it into the lower opening of a tall chimney [6]. Ambient (cold) air enters the collectors from the periphery and is heated as it flows along the collector toward the center. Due to the pressure created by the density difference between the warm airflow and ambient air, the airflow enters the chimney, and with the turbine generator, the kinetic energy of the airflow is transferred into the electrical power. It is based on three simple principles: the solar greenhouse effect, the chimney buoyancy effect and the wind power principle. Accordingly, the solar collector is the heat source, the chimney is the engine, and the turbine generator is the power conversion unit [7].

The collector acts similar to a greenhouse by allowing solar radiation to reach soil surface and heating the above air by convection. The heats travels from soil surface through the space comprised between the collector outside and the chimney base. This in effect heats up the air between the ground and the collector [8].

In most applications, the ground material only acts as a thermal storage system, storing energy during the day and discharging the stored energy during low solar radiation flux such as at night ensuring the solar chimney continue to operates the whole day. In other words, when the ambient temperature is lower than the soil temperature, then soil releases the energy accumulated during the day, heating the air, producing the same buoyancy effects due to air density difference but in this case without the solar radiation acting on the system at that particular time [8].

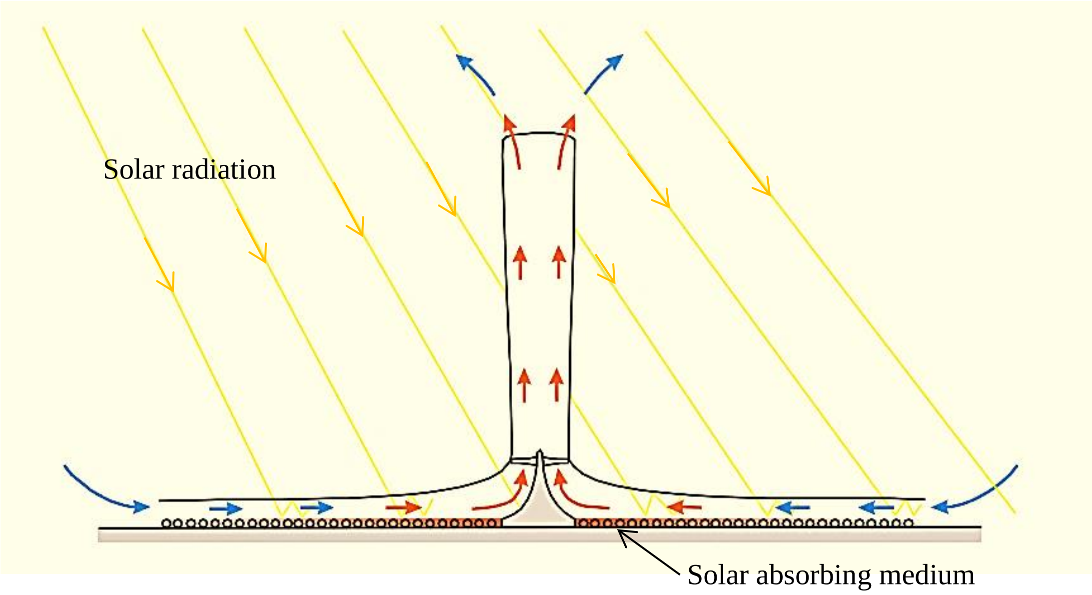

Figure 1 The illustration of the natural convection of air flowing from base/collector updraft the chimney [9].

As presented in the figure above, a solar updraft tower converts solar radiation into electricity by combining three well-known principles: the greenhouse effect, the tower and wind turbines. Hot air is produced by the sun under a large glass roof or cover [10]. The greenhouse effect offers heated air while the tower cause stack effect increasing the air flow velocity. The wind turbine is used to transfer the kinetic energy of the air into mechanical and later electrical energy.

Since solar chimney working principle is converting sun's radiation into thermal energy, its basic configuration was having drawback such as unable to efficiently operational at night. However, this problem was solved by including thermal storage sub-system to the SCPP system that are charged during the day, and discharge the energy during the night to heat up the air.

The chimney itself is the plant's actual thermal engine. It is a pressure tube with low friction loss (like a hydroelectric pressure tube or penstock) because of its optimal surface-volume ratio. The up thrust of the air heated in the collector is approximately proportional to the air temperature rise in the collector and the volume, (the height of the chimney multiplied by its diameter). In a large SCPP, the collector raises the temperature of the air by about 35 K [9].

The ground material having higher absorptivity value will increase the efficiency of converting solar radiation into thermal energy. This will lead to higher temperature increase and kinetic energy. The ground material plays an important role in increasing the thermal performance of the SCPP as it is responsible to absorb as much as solar radiation as possible and converting it into thermal energy heating the working fluid.

In designing a SCPP system, two crucial part of the chimney is the collector and the chimney itself aside from the turbine that responsible to the power generation part of the solar chimney power plant. Their properties in the solar chimney system are explained below.

Collector

The solar tower uses a greenhouse-like effect collector to heat the air that in turn drives the turbine of the power plant. The collector surface gradually rises closer to the tower, to direct the heated air towards the tower as the heated air's density decreases, and then curves up at the base of the tower in order for transition of the air flow up the tower turning the turbine. The collector material can be any glass-like material, with high transparency to the solar spectrum but with low transparency to the infrared radiation emitted from the warmed ground [11]. Direct and diffuse solar radiation strikes the glass roof, where specific fractions of the energy are reflected, absorbed and transmitted [12].

Usually, natural soil is used as the ground material and has a certain thermal storage capacity, but its thermal storage capacity cannot meet the need of solar chimney operation during night time [13]. The ground material is also being utilized as agricultural land due to the greenhouse effect of the collector [14]. From this, it can be concluded that the natural ground of the site that the solar chimney is built is being used as the ground material without much alteration aside from installing additional thermal storage system to ensure continuous operational and agricultural.

Figure 2 A small experimental solar updraft tower plant, built in Manzanares, Spain [14]. As can be seen, it is used as an agricultural land aside from generating electricity.

Chimney

The chimney or tower of a solar chimney is the thermal engine of the plant. The heated air from the collector is funneled into the chimney due to the slanted roof of the collector itself where the buoyancy difference between the heated air and the surrounding atmosphere creates a pressure difference that drives the air up and into the chimney [11].

Several factors contribute to the physical design of the chimney. The chimney should be designed to reduce the frictional losses but maximize the pressure difference in the tower between the outlet and the inlet. The pressure difference in the tower is proportional to its height, so maximizing the height of the tower is critical to improving the efficiency of the tower.

Governing Equations

The solar energy input rate into the system is dependent on the area of the collector and the solar irradiation flux density falls onto the collector area where I is the normalized solar irradiation in W/m^2 [11]:

$$\dot{Q}_{solar} = I \cdot A_{collector}$$

Without a turbine in the tower, all the pressure difference in the tower is converted to velocity of the air itself. The power contained in the flow is then be represent by this equation:

$$P = \frac{1}{2}\dot{m}v^2$$

$$\dot{m} = \rho A_{cross} v$$

$$P = \frac{1}{2}\rho A_{cross} v^3$$

The mass flow rate of air is assumed to be constant for the entire system for a particular moment. The kinetic energy is dependent to the mass flow rate of air which is subject to the temperature the system able to achieve.

Amount of energy utilized by the ground material to heat the air is also evaluated using stated equation.

$$\dot{Q}_{utalized} = (\dot{m} \cdot cp \cdot \Delta T)_{air}$$

The expression of the Collector efficiency is [15]:

$$\eta_{collector} = \frac{\dot{Q}_{utalized}}{\dot{Q}_{solar}} = \frac{(\dot{m} \cdot cp \cdot \Delta T)_{air}}{I \cdot A_{collector}}$$

It is then known that the performance of the solar chimney is ascertained by determining the mass flow rate through the system that will maximize the power output at a particular time that can be drawn by means of turbines.

The basic flow of this experiment for solar chimney is illustrated as follows. This illustration shows the flow of energy from the sun in form of radiation until converted into kinetic energy in the form of moving air.

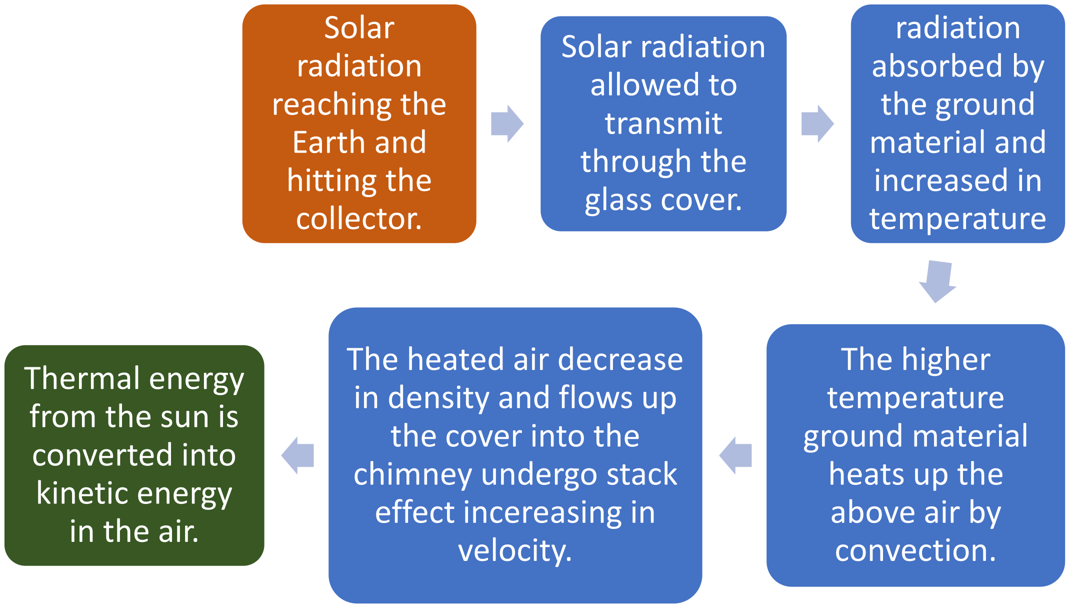

Figure 3 The illustration showing the flow of energy from its source, the sun in form of radiation into extractable kinetic energy of the wind.

The energy supplied by the sun is the input to the system while the rate of energy of the air is considered as the utilized energy. For this experiment, the evaluation is made based on the utilized power ratio to heat the air to the supplied power received by the ground material.

CHAPTER 3

METHODOLOGY

3.1 Designing the Experiment Setup

Due to the experiment being a comparison of several types of ground material, the test need to be carried out simultaneously for all the tested ground materials to ensure similar test condition. Thus, a test rig needs to be designed and fabricated to meet the requirement of the experiment. Concept of the experiment setup rig to test the materials in the most efficient ways considering the time constrain is generated and evaluated.

Furthermore, the test system must contain the components that make up a SCPP system such as the collector and the chimney. The test rig must be able to duplicate the environment of the system in a parallel configuration so that all the test material can be tested under similar condition. This is important to evaluate the performance of these materials and also reduce the amount of time required to achieve the experiment objective of characterizing the absorptivity of these ground materials.

Decision tree illustrates the design stage of the experimental work form generating concept of the test rig design to producing the technical drawing of the required parts.

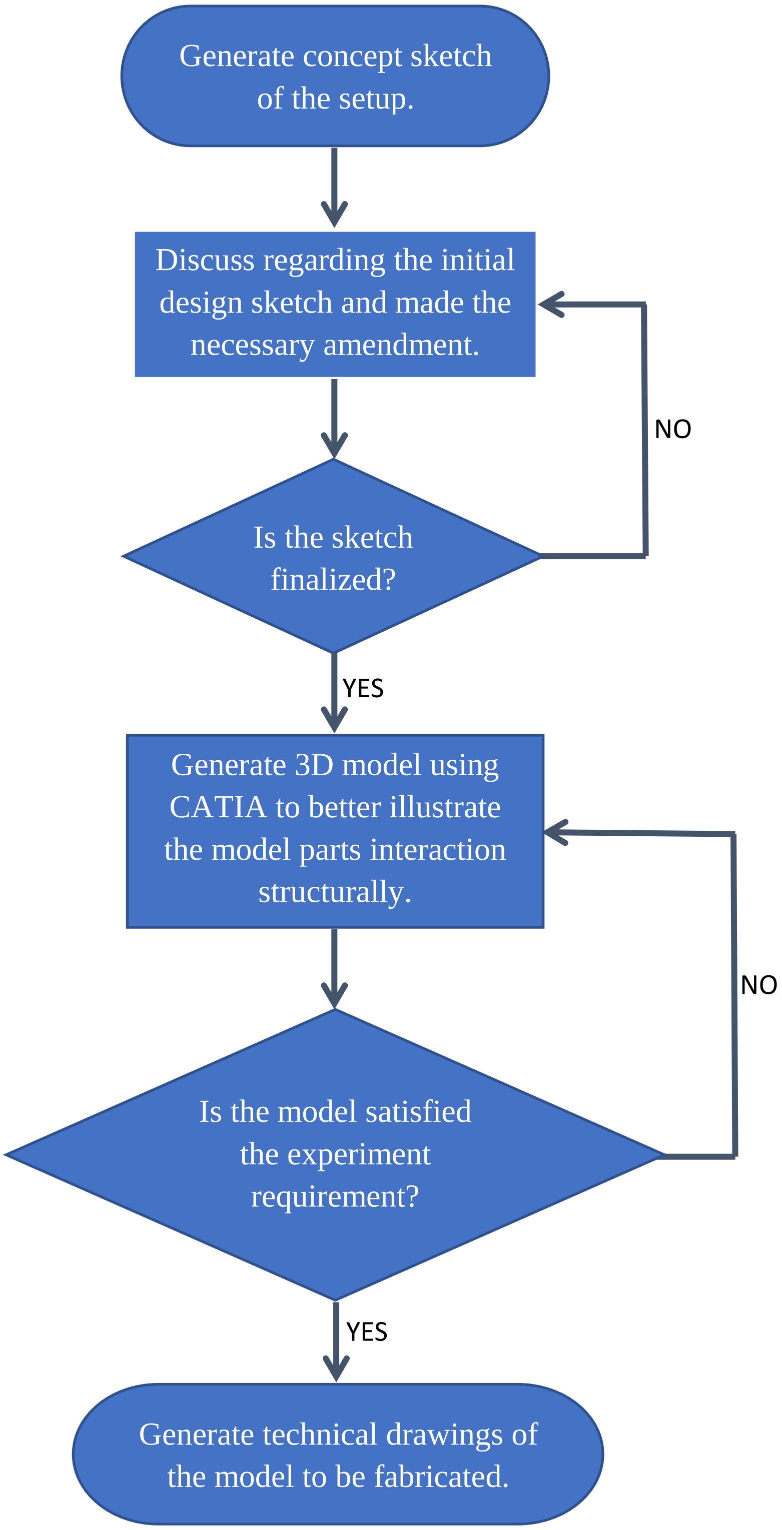

Figure 4 Decision tree illustrating the process of concept generation of the test rig for the experiment.

Concept Generation:

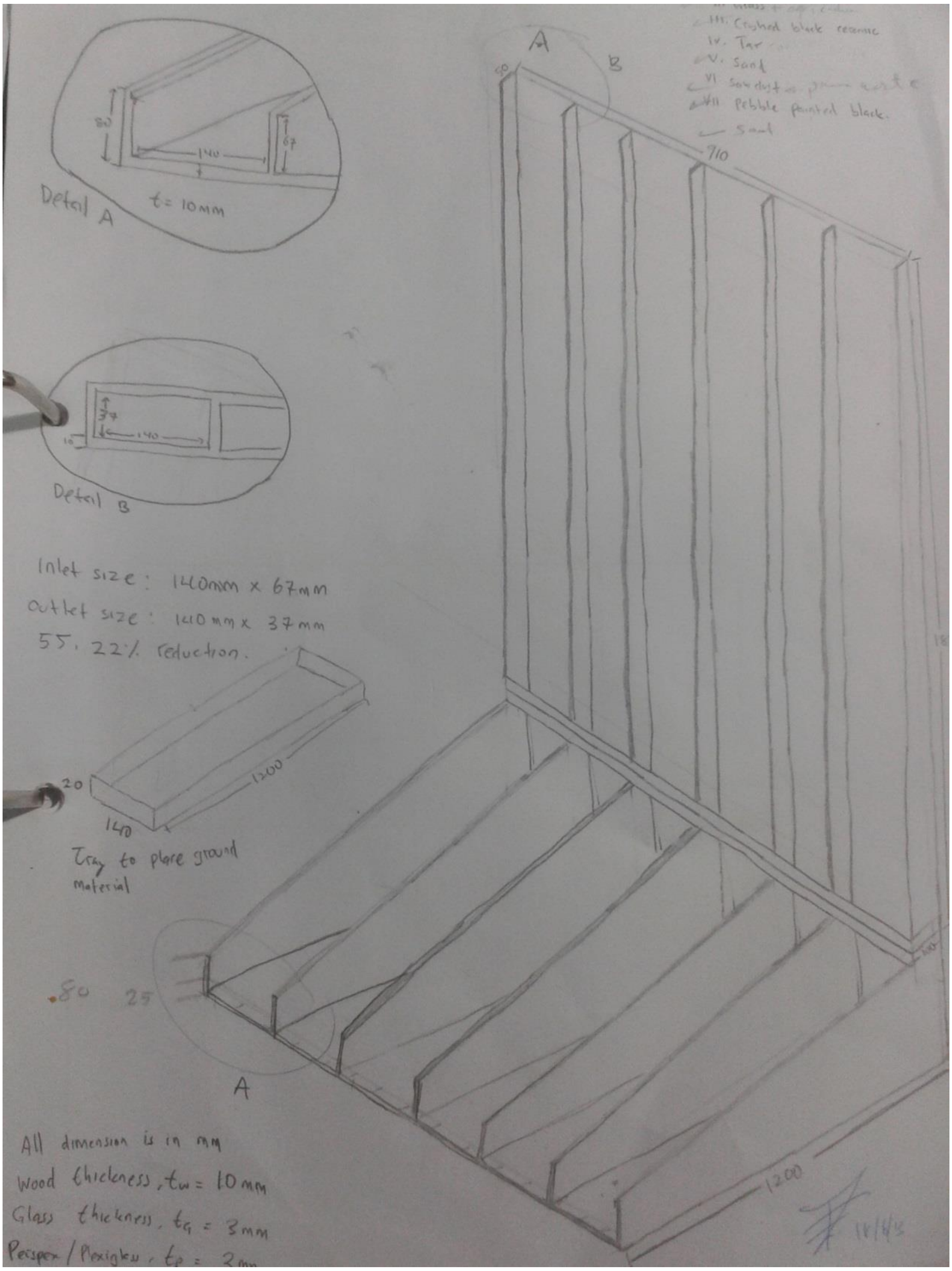

Figure 5 Initial sketch for conceptual design of the experiment setup.

3d CAD Model Generation:

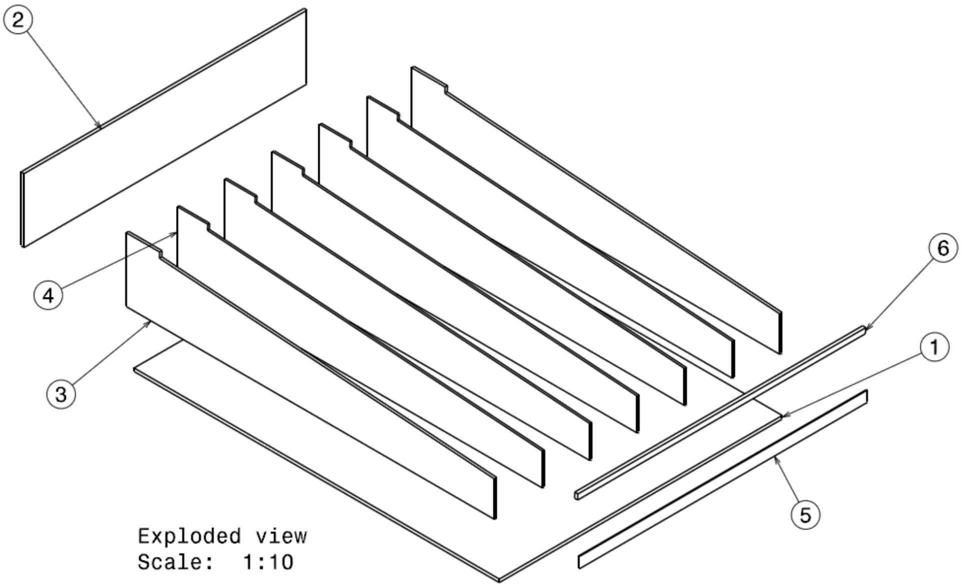

Figure 6 Illustrated of the exploded view of the collector base model.

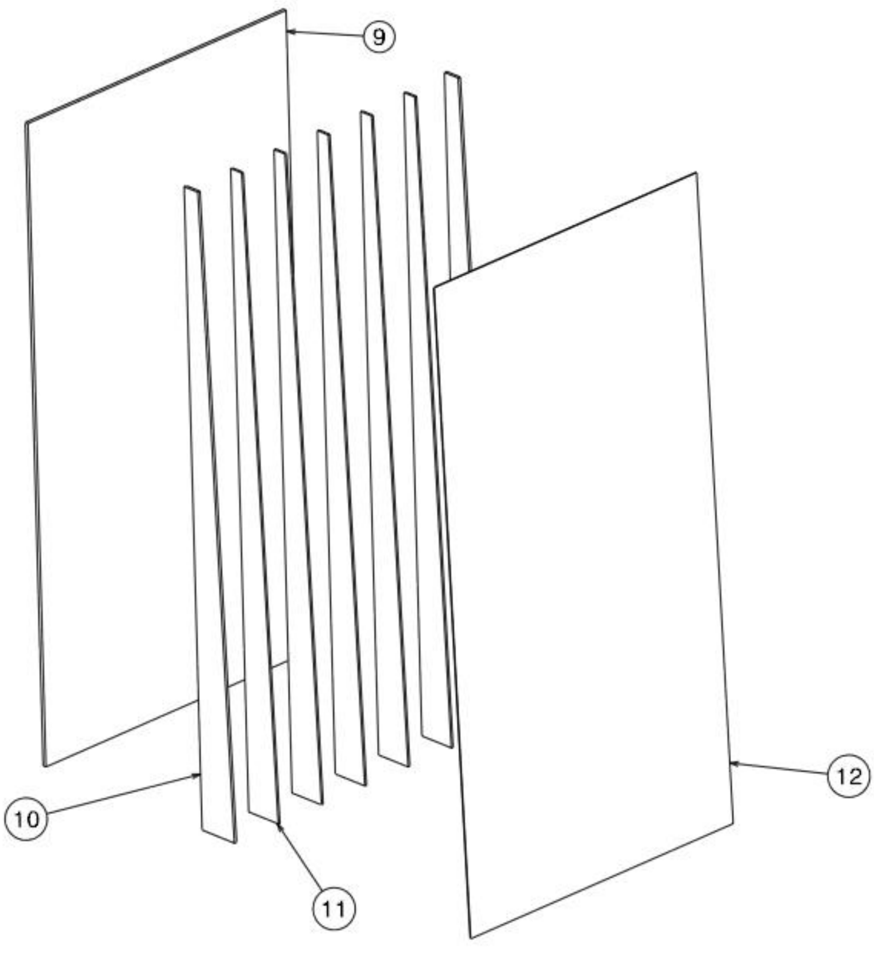

Figure 7 Illustrated of the exploded view of the chimney part model.

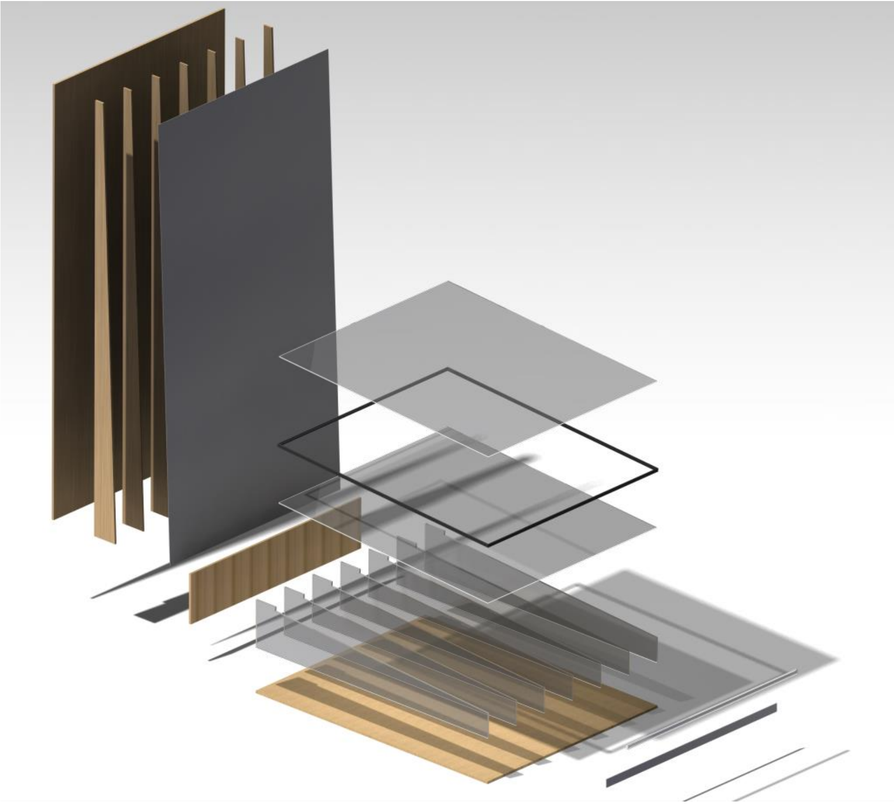

Figure 8 Exploded view of the test rig designed using 3D modelling software.

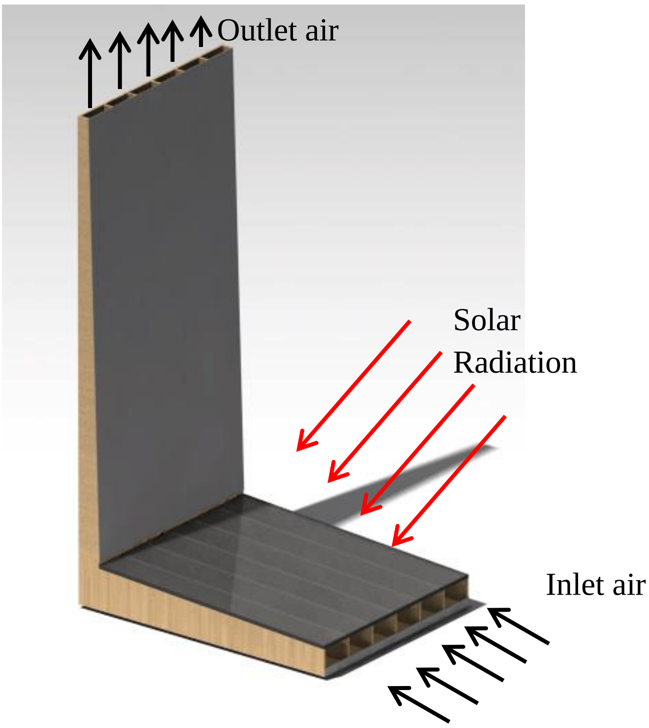

Figure 9 Assembled view of the test rig rendered by CATIA.

3.2 Fabrication

The fabrication is when the finalized design is materialized using the specified material. The sensors and other features and final customization to the experiment rig are also done in the fabrication stage. Below is the breakdown of the fabrication process.

1. Sent the rig design to be fabricated (outsource).
2. Follow up on discussion on the rig physical development.
3. Perform protection task (wood treatment and painting) to the rig as it arrived to the site.
4. Setup the sensors onto predetermine points.
5. Prepare additional setup and housing for safe-keeping of recording instrument during experimental run.

Figure 10 The setup at the fabricator's shop; view 1.

Figure 11 The setup at the fabricator’s shop; view 2.

The test rig or setup is then weather protected and sealed between each slot to minimize interference from the adjacent material testing slots. Sensors were installed at respective point to measure and record the desired data.

Figure 12 The setup at the solar site.

Figure 13 The setup at the solar site after setup facing south.

3.3 Obtaining the Test Materials

The six (6) test materials for ground material of the base/collector are obtained and prepared for the progress of the experiment. Some of the materials are self-prepared while others are used as it is.

A) Crushed Black Ceramics

B) Sand

C) Pebbles Painted Black

D) Sawdust

E) Painted Stone (Crusher Run)

F) Wooden Plywood (Changed from green leaves since deemed unsuitable)

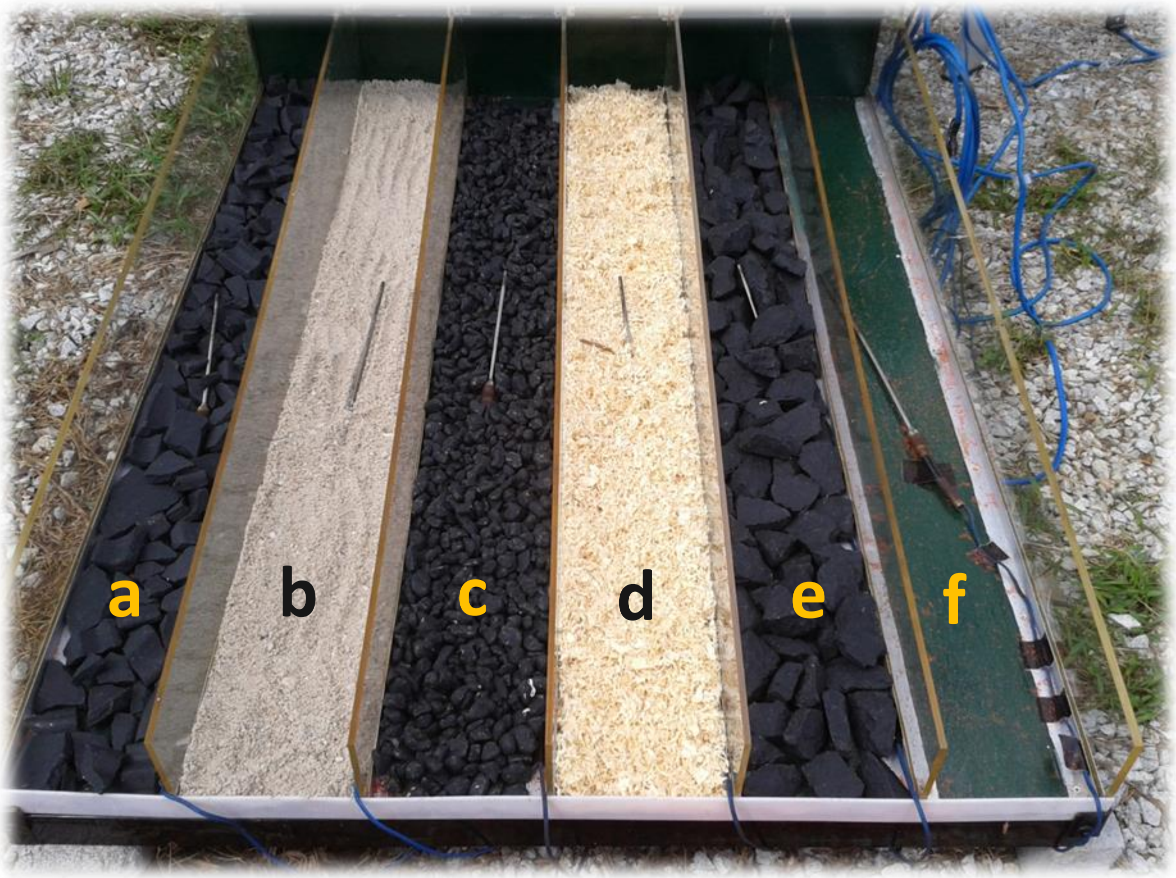

Figure 14 The test materials being lined up in their respective compartment. The thermocouples are not yet fixed to the its' stand.

3.4 Conducting the Experiment

The experiment is conducted to gather the required data of the system. The test rig is positioned at the site as predetermined and all sensors are connected and checked for error. The data collection is done automatically with the use of data logger and manually with an hourly measurement reading. The procedures of the experiment are as stated:

1. Place the setup of the experiment at site with the inlet opening facing the South.
2. Lay the ground materials to be tested in their respective slot.
3. Close the enclosure panel and secure the setup.
4. Connect the thermocouples at the designated position to a data logger.
5. Set the data logger to collect data measured at 30 minutes intervals for 12 hours.
6. Begin recording the data of the experiment from 8.00 am until 7.00 pm. using data logger.
7. Velocity of the outlet air is measured by means of vane type air anemometer and hot wire anemometer as cross reference to the calculated velocity.
8. Repeat the procedure for 3 days.
9. Analyze the data sets obtained.

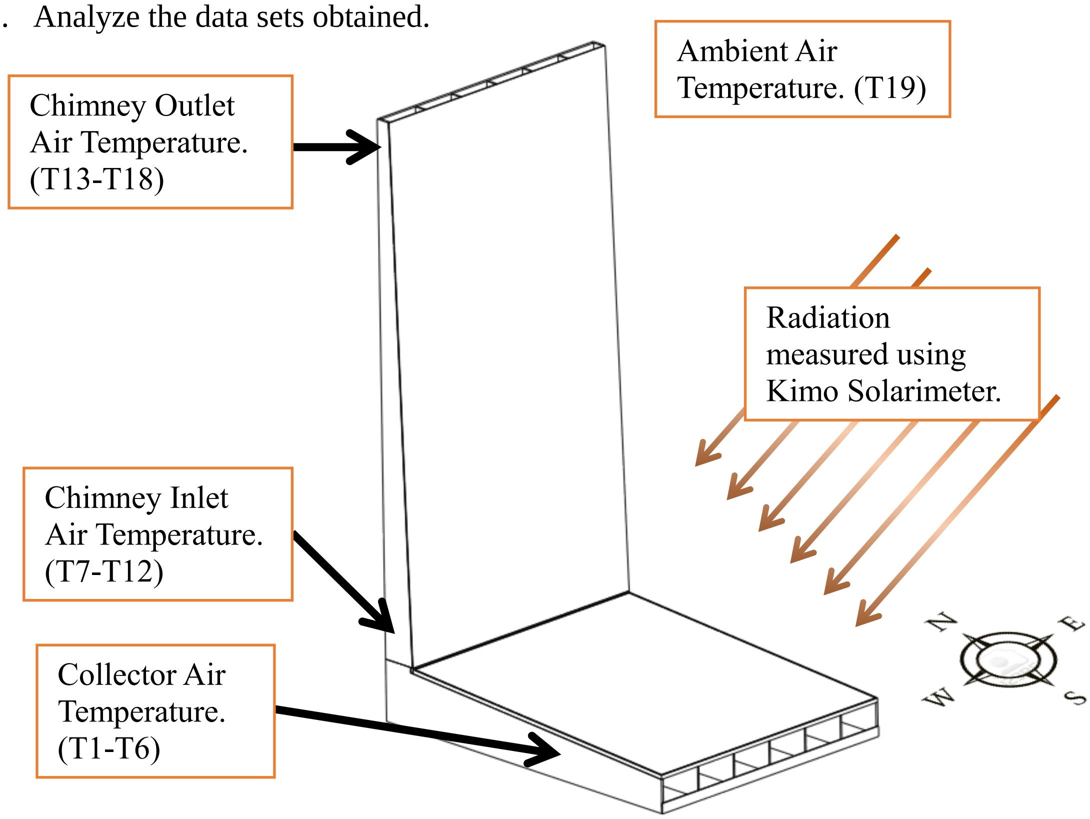

Figure 15 Illustration showing the position of the measurement points on the test rig for the experiment.

3.5 Instruments Used

Automatic and manual measurement methods are both applied for this experiment. The use of digital measuring instrument and programmable data logger is to reduce the strain on the operator and increase the reliability of the data recorded due to long duration of experiment. Stated below are the instruments used for this particular experiment.

- Graphtec Data Logger GL820

Figure 16 Data logger used for the experiment, GL820

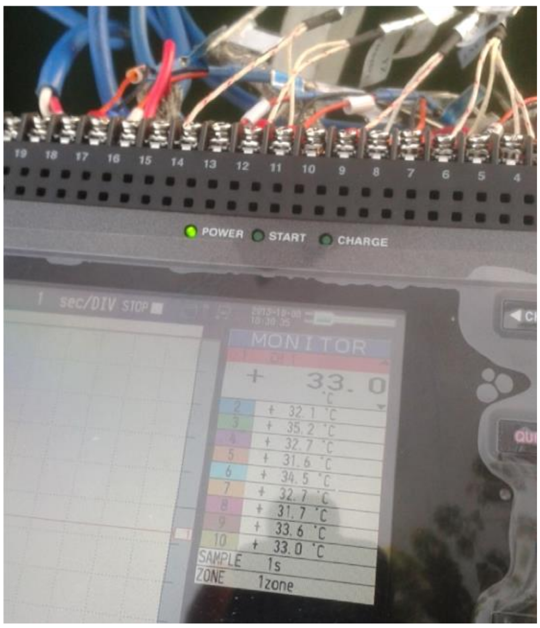

Figure 17 19 channels for the temperature readings were logged by the data logger.

➢ Kimo Solarimeter SL200

Figure 18 Solarimeter measure and log the solar radiation available for the duration of the experiment.

➢ Kimo Vane Type Anemometer

Figure 19 Wind velocity measured at the outlet opening of the chimney to be verified with the mathematical calculations.

- Kimo Hotwire Type Anemometer

Figure 20 Hot wire anemometer is used to reduce the interference of cross wind during measuring.

3.6 Analysis of Experimental Data

For the analysis of the recorded experimental data, these sets of equations and methods are used to produce the result and graphs. This is based on the energy that is supplied by the sun and the ability of the ground material to convert the radiation energy into thermal energy used to heats up the air by convection. Chimney effect can also be calculated based on the chimney parameter to mathematically obtain the air velocity of the system. This chimney effect is suitable as the real-time wind measurement is done and founded that the inference from the environment is unsteady and deemed unsuitable.

1. The volume flow rate of the air is calculated.

$$\dot{V} = C \cdot A_{chimney} \cdot \left[2 \cdot g \cdot h \cdot \left(\frac{T_i - T_a}{T_i}\right)\right]^{0.5}$$

$\dot{V} = Stack\ effect\ draft\ \ flow\ rate, m^3/s$

$A = Flow\ area\ cross - section, m^2$

$C = Discharge\ coefficient\ (usually\ taken\ to\ be\ from\ 0.65\ to\ 0.70)$

$g = Gravitational\ acceleration, 9.81\ m/s^2$

$h = Height\ of\ chimney, m$

$T_i = Inside\ temperature, K$

$T_a = Outside\ temperature, K$

2. The air velocity is calculated at the exit point.

$$V = \frac{\dot{V}}{A_{chimney}}$$

$V = Air\ velocity, m/s$

$A = Flow\ area\ cross - section, m^2$

$\dot{V} = Air\ \ flow\ rate, m^3/s$

3. Air density is calculated using ideal gas law.

$$\rho = \frac{P}{R \cdot T}$$

$\rho = \ Air\ density,\ \ kg/m^3$

$P = \ Pressure, Pa$

$R = \ Specific\ gas\ constant\ for\ air\ is\ 287.058, J/(kg \cdot K)$

$T = \ Temperature\ of\ the\ air, K$

4. Mass flow rate of air calculation is done.

$$\dot{m}_{air} = \rho \cdot A_{chimney} \cdot V$$

$\dot{m}_{air} = Mass\ flow\ rate,\ \ kg/s$

$\rho = \ Air\ density, kg/m^3$

$A_{chimney} = \ Flow\ area\ cross - section, m^2$

$V = \ Air\ velocity, m/s$

5. Energy absorbed rate by ground material and transferred to the air.

$$\dot{Q}_{utalized} = (\dot{m} \cdot cp \cdot \Delta T)_{air}$$

$\dot{Q}_{utalized} = Energy\ transfered\ to\ air, W$

$\dot{m} = Mass\ flow\ rate\ of\ air, \qquad kg/s$

$cp = \ Air\ specific\ heat\ capacity, J/kg \cdot K$

$\Delta T = \ Temperature\ difference, K$

6. Energy supplied rate to the system.

$$\dot{Q}_{supplied} = I \cdot A_{collector}$$

$\dot{Q}_{supplied} = \text{ } Energy\ supplied\ by\ the\ sun, W$

$A = \text{ } Collector\ area, m^2$

$I = \text{ } Solar\ radiation$

7. Thermal efficiency of solar chimney system.

$$\text{Efficiency}, \eta = \frac{\dot{Q}_{utalized}}{\dot{Q}_{supplied}} = \frac{(\dot{m} \cdot cp \cdot \Delta T)_{air}}{I \cdot A_{collector}}$$

3.7 Conducting the Simulation

Simulation need to be performed to observe the behavior of the setup in a more controlled environment. Ansys-FLUENT software is chosen and simulation needs to be carried out.

The simulation is done from the obtained figures from the experiment and analyzed using the software to visualize the response of the system with the data inputted.

Since computational power is an issue, highly complex simulation taking into account all possible variable and precise mesh of the model is unavailable. This simulation is intended to be used as comparison to the practical experimentation data.

Boundary condition such as mass inlet, mass outlet, radiation at the collector glass cover, ground material and walls are defined. Parameters were set allowing the system to be simulated.

Four points in the timeframe was simulated which are, 9.00 am, 12.00 pm, 3.00 pm and 6 pm. This is to ensure the behavior of the system at different moment is better illustrated and understand.

3.8 Gantt Chart and Key Milestones

Project Gantt Chart and Key Milestone

Activities	Week																									
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26
Title Awarded	X	X																								
Understanding Project Objective			X																							
literature Reviews			X	X																						
Designing the Experimental Setup				X	X	X																				
Fabrication							X	X	X																	
Obtaining Test Materials									X																	
Conducting the Experiment																										
"Rig Setup & Dry Run"										X	X	X														
"Conducting Test"													X	X												
Result Compilation and Conclusion															X	X	X	X	X	X	X	X				
Documentation																										
"-Extended Proposal"				X	X	X																				
"-Interim Report"											X	X	X	X												
"-Progress Report"																		X	X							
"-Dissertation"																							X	X	X	
"-Technical Paper"																							X	X	X	

Key Milestones

CHAPTER 4

RESULT & DISCUSSION

4.1 Experimental Result

After repeated experimental data were obtained, the data were screened and analyzed as stated previously. These data are crucial to evaluate the state and condition of the experimental rig, the performance of the rig in general and also evaluating the characteristic of the tested ground material to be use in solar chimney application. Data logger recorded the temperature variation throughout the 11 hours experiment daily for three days. Solarimeter was used with built in logger and responsible to record the radiation value at the pre-set condition. Average values were then calculated to provide a better accuracy result of the experiment. Based on the temperature graph of these ground materials, we could calculate its performance and efficiency of the material to utilize the radiation energy supplied by the sun. Tables below shown the average data collected for the experiment:

Time	Radiation	Collector Inlet Air Temperature (Deg C)					
Hourly	W/m2	Ceramic	Sand	Pebble	Saw Dust	Stone	Plywood
8:00:00	73.3	25.9	25.6	26.0	26.4	26.5	27.8
9:00:00	186.3	30.3	30.3	30.5	30.8	30.9	33.7
10:00:00	347.3	36.2	35.8	36.0	35.5	36.0	39.1
11:00:00	385.0	39.0	38.7	38.8	38.2	39.5	40.8
12:00:00	529.3	44.3	44.0	44.0	43.1	44.4	45.5
13:00:00	436.0	43.7	43.3	43.6	42.8	44.6	45.1
14:00:00	369.3	42.7	42.1	42.6	41.8	43.4	43.8
15:00:00	355.0	41.4	41.0	41.6	41.4	43.1	43.3
16:00:00	319.3	39.9	38.8	39.3	38.9	40.6	40.4
17:00:00	268.7	39.2	37.7	38.4	38.0	38.9	40.0
18:00:00	113.7	36.4	33.5	33.3	33.0	34.2	33.7
19:00:00	0.0	29.0	28.4	29.0	28.4	29.6	28.6

Table 1 Collector air inlet temperature for each of tested materials.

The readings obtained were of the air temperature inside the collector. This air is being heated by the ground materials by means of convection mostly. The higher temperature increase is the first indication of the ground material absorptivity characteristic however; decision cannot be made prior to analysis of these data as the performance is not clearly justified. Higher temperature will provide better pressure difference in the chimney later on due to stack effect.

Time	Radiation	Collector Outlet/Chimney Inlet Air Temperature (Deg C)					
Hourly	W/m2	Ceramic	Sand	Pebble	Saw Dust	Stone	Plywood
8:00:00	73.3	24.6	24.7	25.0	25.3	25.1	25.5
9:00:00	186.3	27.8	27.4	27.8	28.1	28.3	29.2
10:00:00	347.3	32.5	31.8	32.3	32.2	32.9	33.7
11:00:00	385.0	36.2	35.1	35.8	35.4	36.5	36.3
12:00:00	529.3	40.9	39.4	40.7	39.7	41.1	40.4
13:00:00	436.0	41.1	39.5	40.7	39.8	41.4	40.3
14:00:00	369.3	40.3	38.7	40.0	38.8	40.8	39.3
15:00:00	355.0	39.3	37.8	39.2	38.4	40.0	38.9
16:00:00	319.3	38.2	36.5	37.6	37.2	38.5	37.2
17:00:00	268.7	37.8	35.3	36.4	36.1	37.0	36.1
18:00:00	113.7	34.9	33.1	33.6	33.3	34.1	32.9
19:00:00	0.0	29.5	29.0	29.5	29.7	30.1	29.1

Table 2 Collector air outlet temperature for each of tested materials.

Time	Radiation	Chimney Outlet Air Temperature						Ambient
Hourly	W/m2	Ceramic	Sand	Pebble	Saw Dust	Stone	Plywood	Temp (Deg C)
8:00:00	73.3	25.1	24.7	25.5	26.0	25.5	26.0	25.5
9:00:00	186.3	28.9	27.9	28.4	29.0	28.3	29.5	27.3
10:00:00	347.3	32.4	32.4	32.6	32.2	32.8	33.7	28.1
11:00:00	385.0	35.6	35.9	35.3	35.1	36.4	36.5	29.1
12:00:00	529.3	39.6	39.6	39.3	39.1	40.5	40.3	30.8
13:00:00	436.0	40.2	40.2	39.9	39.7	41.1	40.5	31.3
14:00:00	369.3	39.1	38.8	39.6	38.7	40.0	39.2	30.6
15:00:00	355.0	39.1	38.2	38.6	38.5	39.6	38.9	31.4
16:00:00	319.3	38.3	36.4	37.7	37.3	37.9	37.5	30.7
17:00:00	268.7	39.7	36.2	36.7	37.1	37.4	36.8	32.6
18:00:00	113.7	36.0	33.9	33.3	33.9	34.3	33.4	31.0
19:00:00	0.0	29.2	28.8	29.8	29.9	29.9	29.4	28.1

Table 3 Chimney air outlet temperature for each of tested materials and ambient temperature.

For Table 2 and Table 3, readings of the air temperature inside the chimney are recorded. This air will drive the stack effect inside the chimney that will drive the air flowing upwards. The air temperature will have an effect on the air velocity inside the chimney. Larger variation between the inside temperature to the ambient will create a bigger pressure difference that would lead to higher air flow rate being discharge from the chimney top.

Ceramic								
Time	Chimney Air Temp Average (Deg C)	Flow Rate, Q(m3/s)	Velocity (m/s)	Air Density (kg/m3)	Mass Flow Rate (kg/s)	Radiation through glass cover (W/m2)	Enery Absorb Rate by Material (W)	Energy Transfer Rate to Air (W)
8:00:00	24.83	#NUM!	#NUM!	1.19	#NUM!	73.3	13.2	#NUM!
9:00:00	28.37	0.0014	0.23	1.17	0.0017	186.3	33.54	5.01
10:00:00	32.45	0.0029	0.46	1.16	0.0034	347.3	62.52	27.31
11:00:00	35.93	0.0037	0.58	1.14	0.0042	385.0	69.3	41.35
12:00:00	40.25	0.0043	0.68	1.13	0.0048	529.3	95.28	65.38
13:00:00	40.68	0.0043	0.67	1.13	0.0048	436.0	78.48	59.04
14:00:00	39.70	0.0042	0.66	1.13	0.0048	369.3	66.48	57.68
15:00:00	39.20	0.0039	0.61	1.13	0.0044	355.0	63.9	44.13
16:00:00	38.22	0.0038	0.60	1.13	0.0044	319.3	57.48	40.05
17:00:00	38.73	0.0035	0.54	1.13	0.0039	268.7	48.36	25.70
18:00:00	35.45	0.0030	0.47	1.14	0.0034	113.7	20.46	18.29
19:00:00	29.33	0.0016	0.25	1.17	0.0018	0.0	0	1.59

Table 4 Test material calculations done using spreadsheet application based on defined equations.

Early in the day, the system is not yet operating as it is being covered, thus the value for energy transfer to air basically zero. The air temperature of air in the system is similar to the ambient temperature. For the second reading, the system began to transfer energy from the sun to the working fluid.

Using the formulae mentioned previously in the methodology section, the data obtained can be analyzed and the energy utilized can be compared to the energy supplied by the sun in order to calculate its efficiency. These calculated results from the obtained data were then plotted to illustrate the behavior of the system with respect to certain criteria. Graphical illustration of the system behavior throughout the experiment gives better understanding compared to the numerical representation.

Since the ground materials were modified from available raw material, the exact absorptivity factor is unknown. Hence, the input energy rate was measured by the collector area alone. However, the value obtained is sufficient to evaluate the performance of the solar chimney thus the performance of the ground material.

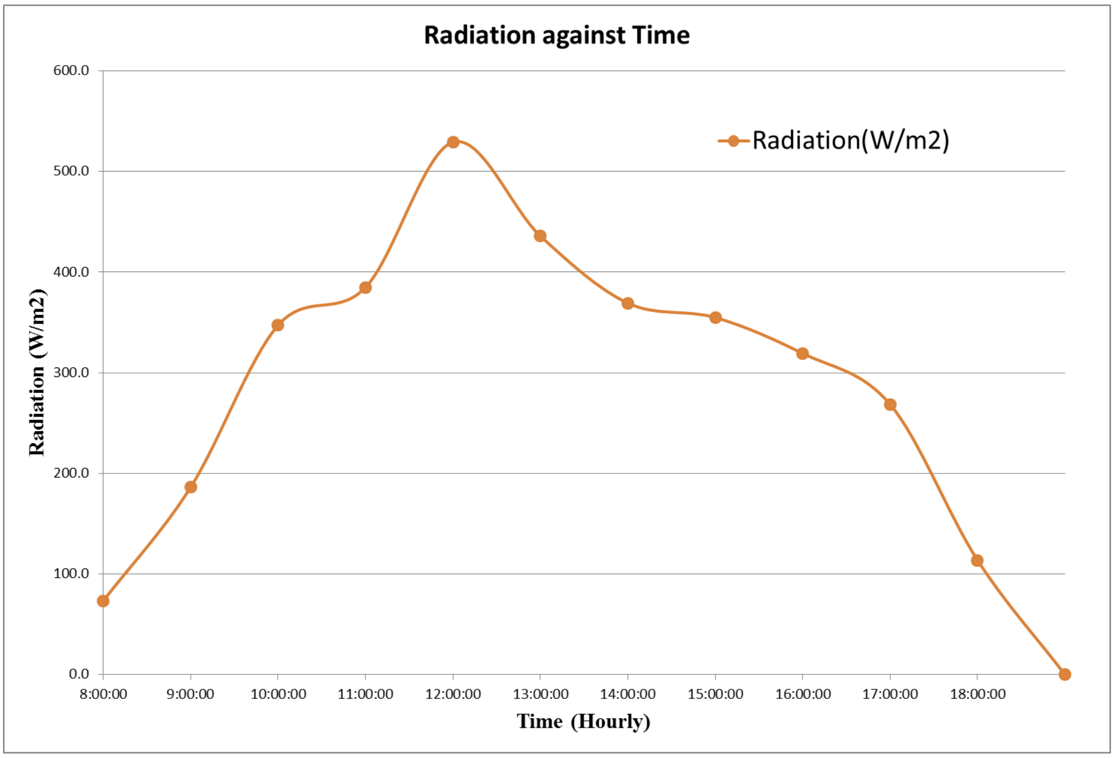

Figure 21 The result of radiation as mean of 3 days.

The radiation curve shown by the graph in not as ideal curve as in Malaysia during this time of the year (October), the peak solar radiation obtained is not at its yearly peak. In typical radiation curve, the highest peak is at the middle of the day which is around 12 pm to 1 pm and expected radiation value is to increase and decrease before and after the peak point. This behavior can be seen in this experiment solar flux readings. However, the cloud plays a role in the collected solar radiation as it would cover the experimental region causing sudden drops in the solar radiation reaching the experimental rig. This radiation pattern affects the behavior of the experiment rig and setup. Thermal storage properties of each of the material tested will provide energy when the solar radiation is declining. This effect can be seen as the efficiency of the chimney increases during the low radiation reading as some of the energy supplied to the air is from the natural thermal storage capability of these tested ground materials. This effect will be further discussed later in the paper.

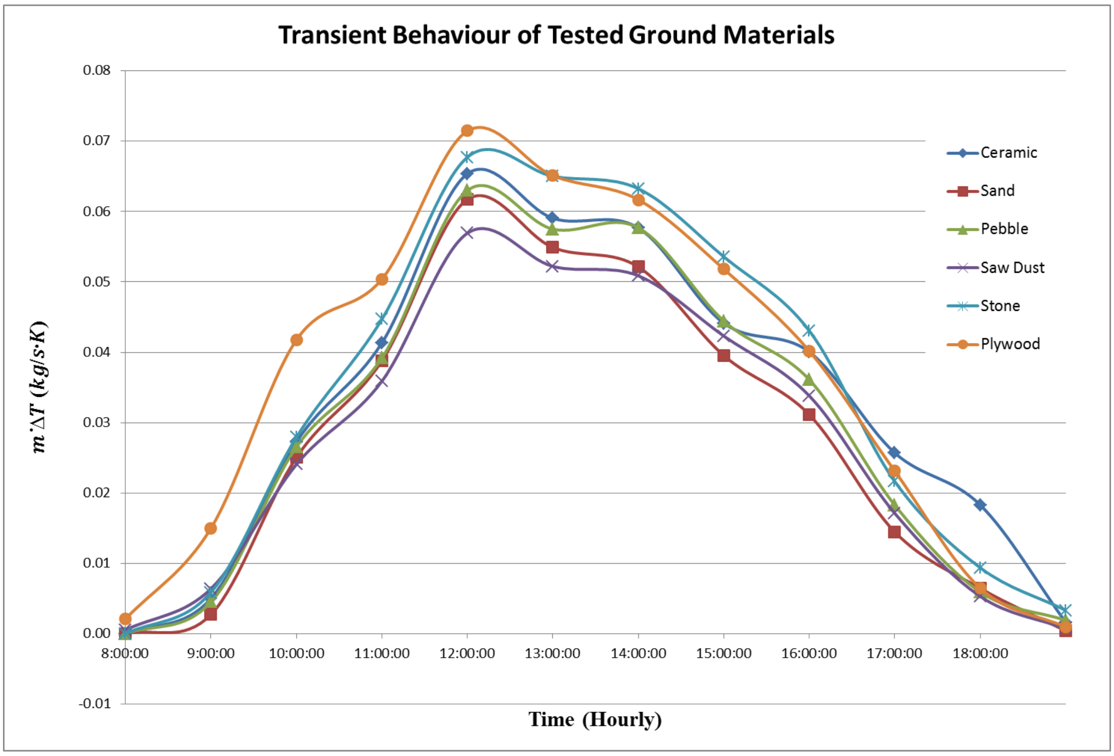

Figure 22 The transient behavior of the compartments.

The graph of the performance of the tested ground material can be seen almost identical to the solar radiation profile. This is because the rig performance increase as the input energy rate increases. More energy supplied by the sun will further increase the temperature of the air flow, causing greater natural convection phenomenon occurring for the respective chimney slot. As the radiation level decreases, the performance value also decreases accordingly.

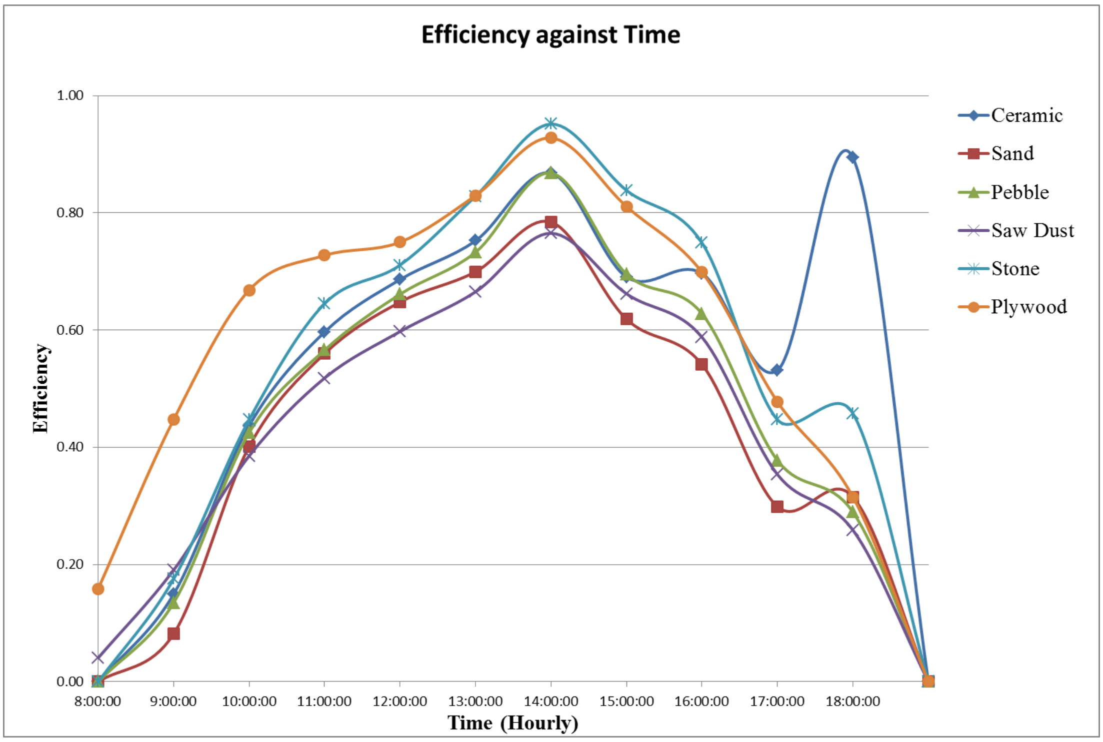

Figure 23 The graph of efficiency against time.

For the efficiency aspect of this experiment, it can be seen that the efficiency varied through time, non-identical to the radiation profile. This is due to the thermal storage capability that the ground materials naturally acquired. During lower radiation capture, the energy stored in the materials is released into the air increasing the calculated efficiency data.

The plywood seems to be more efficient during the early of the experiment whilst the ceramics is during the end of the experiment. Other material poses a quite similar behavior to the condition with variations in their respective values.

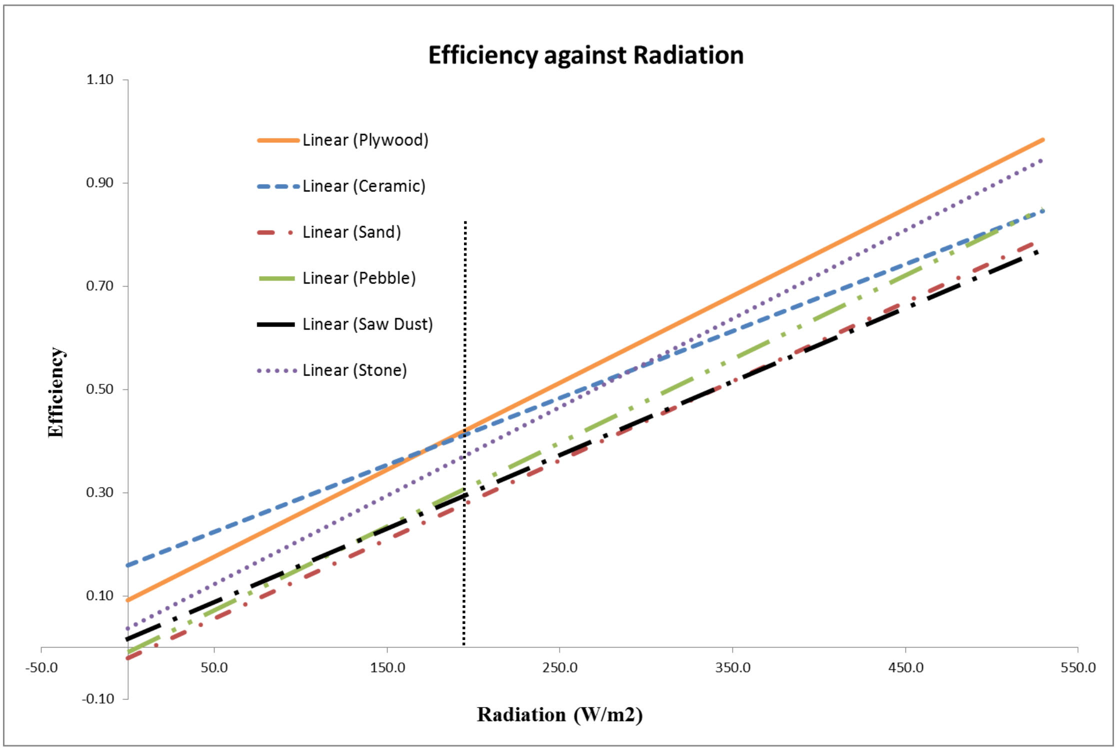

Figure 24 The graph of efficiency against radiation.

As seen plotted on the graph above, painted ceramics ground material has the highest efficiency for a low radiation range and the painted plywood is having the highest efficiency for a higher radiation range value.

The efficiency of the stones is in below the plywood's with the stone's efficiency increase above the ceramics with increase radiation value. Other materials performance and efficiency is graphed lower from these three as can be read from the graph itself.

The thermal storage capability is affecting the efficiency value as higher thermal storage capacity or capability material will has lower efficiency during high radiation level compared to a lower thermal storage capacity materials. This is due to the amount of energy needed to be stored first before being supply to the working fluid.

From the data obtained, calculations were made to come up with performance and efficiency curve with respect to time and temperature change per radiation flux strength. However, the result is differs from other papers being read about. This difference comes from several factors.

Firstly, the radiation value was recorded in a minute interval with device that measures at frequency of 2 readings per second. The solarimeter is able to record all the changes in the solar radiation value. With the climate changing all the time due to clouds, the recorded value for solar radiation is close to real-time value. However, the thermocouples work differently when it records the temperature of the air. There are time lag between the radiation value and the temperature of the air. This is because it takes time to transfer the energy capture by the ground material to the air that travels to the thermocouples. Taking into consideration hysteresis factor on the system, we may obtain result that shows the efficiency of the system at some given moment if to be close to a 100%.

Besides that, there is also suspected gaps between the slotted zones for any particular tested ground material. The gap may exist between the slot barrier walls and the glass cover. The gap was expected to be minimal however; its effect for an 11 hours experiment is somewhat unknown at the beginning and may be taken for granted. The air gap, if being large enough can be an interference to the behavior of its adjacent test material, as gust of air may flow pass the barrier which was design only to allow radiation flow and being thermally and physically insulated. Weather stripping was needed to close the gap in order to further minimize interference to the result obtained.

4.2 Simulation Result

The velocity profiles of compartment containing ceramics are simulated at 9 am, 12 pm, 3 pm and 6 pm intervals.

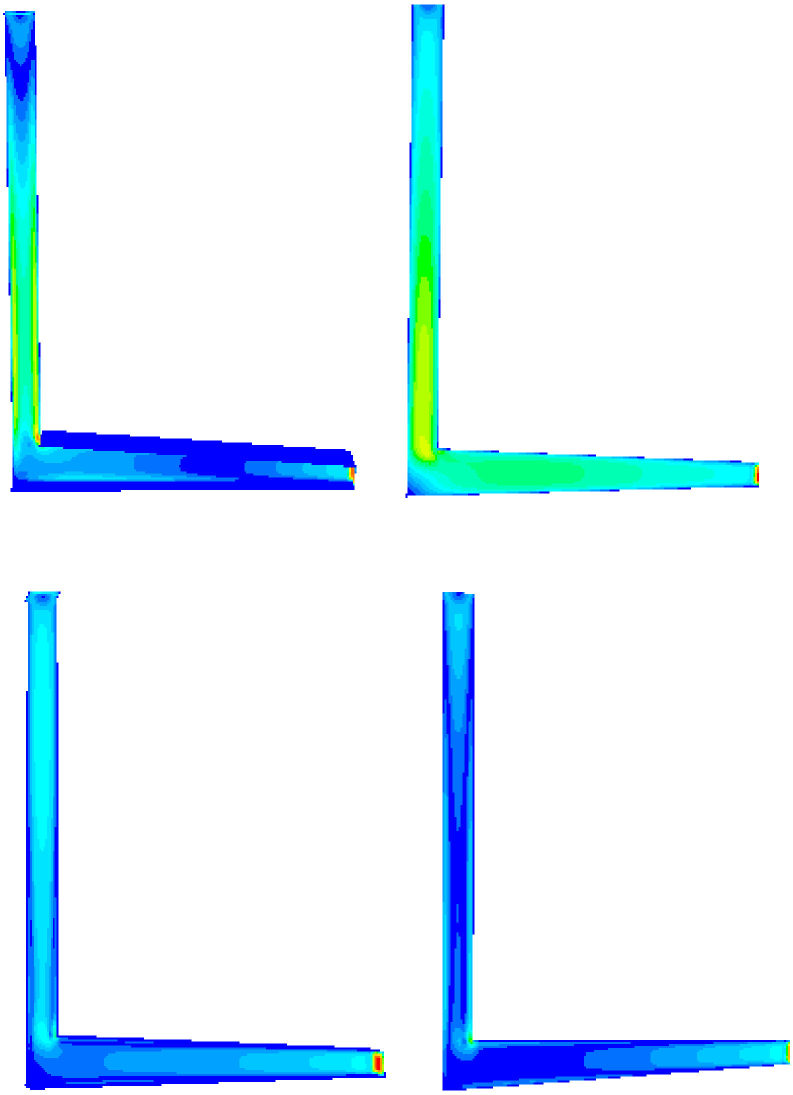

Figure 25 From left to right, top to bottom. The air velocity result of simulation for ceramic at 4 time frames.

As seen, the velocity inside the system starts to build up as the day approach the afternoon (12 pm) and declining as the experiment proceeded further until the end of the day. Similar behavior is seen on the other materials which increases toward the afternoon and started to decline afterwards. This is due to the radiation level availability at the moment. Higher radiation level causes the system to operate at higher temperature hence generating higher velocity flow inside the chimney.

The temperature profile of 6 compartments of test material are simulated at 12 pm is shown below.

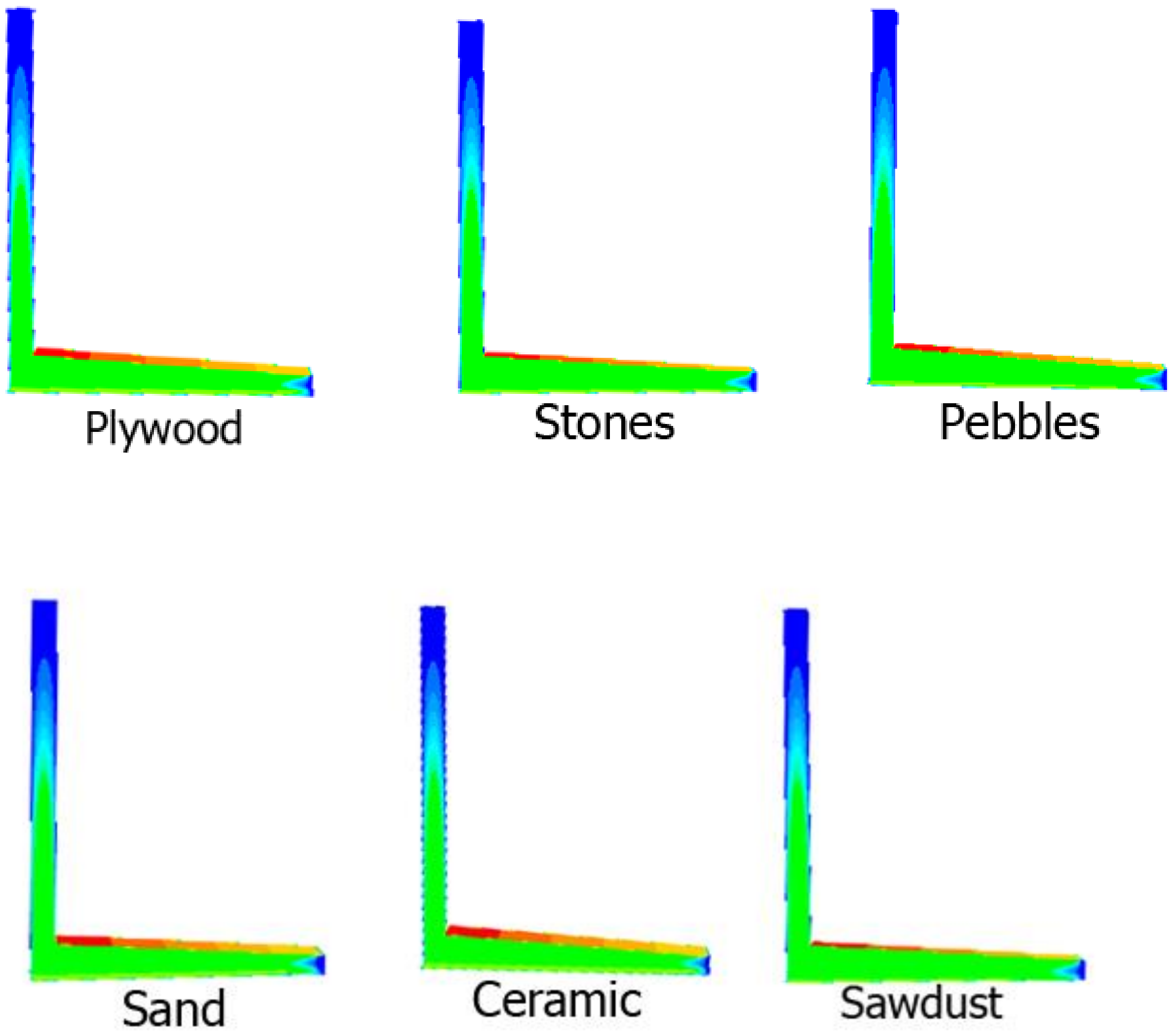

Figure 26 Temperature profile of the test material compartment at 12 pm.

Variation is minimal from one material to another as the temperature difference is slight. As shown:

Temperature of air inside collector at 12 pm (Deg C)					
Ceramics	Sand	Pebbles	Sawdust	Stones	Plywood
44.3	44.0	44.0	43.1	44.4	45.5

Table 5 Temperature of air inside the collector at 12 pm

Similar to the raw experimentation data, conclusion on the tested ground materials simulated performance cannot be produced as the variation in temperature is small considering the scale of the test rig. However, from the numerical data, we can predict that the plywood is preforming the best from the other.

From the simulation, the behavior of the system is observed to be quite similar as the experimental and theoretical ones. The air velocity increases as more energy is being supplied to the air and vice versa. However, evaluation based on the simulation data alone is inadequate as the results obtained are the response of the system towards input. The slight variations in temperature of the air for each tested materials produce small differences in the graphical representation of the system response.

In real world, the system will behave slightly different due to other variable not being considered in the simulation's parameter. However, the simulation has given an insight and act as check and balance mechanism for this project. Concrete conclusion can be obtained once the experimentation data is analyzed further. Since the project is mainly focused on the experimental works in evaluating the tested ground materials, the data evaluation based on the experimental works is given higher priority in characterizing the materials as ground material form solar chimney applications.

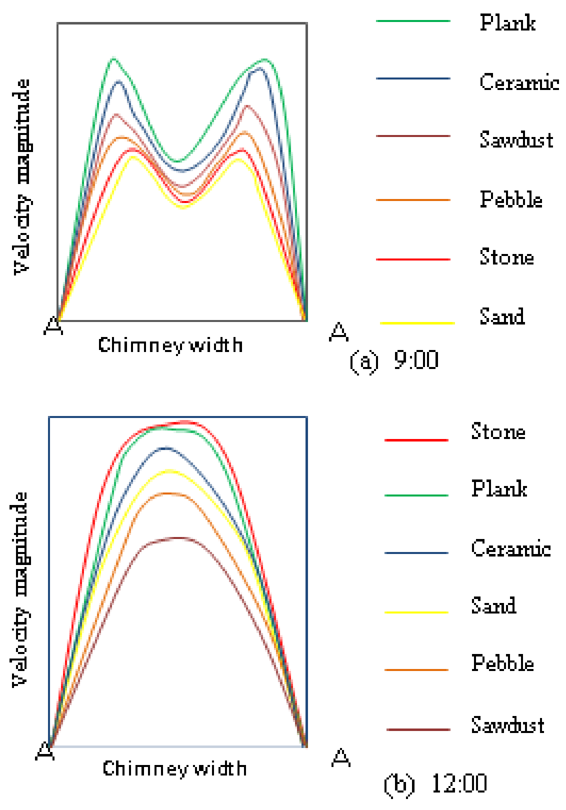

Figure 27 The cross section velocity profile of the test material simulation (9 am and 12 pm).

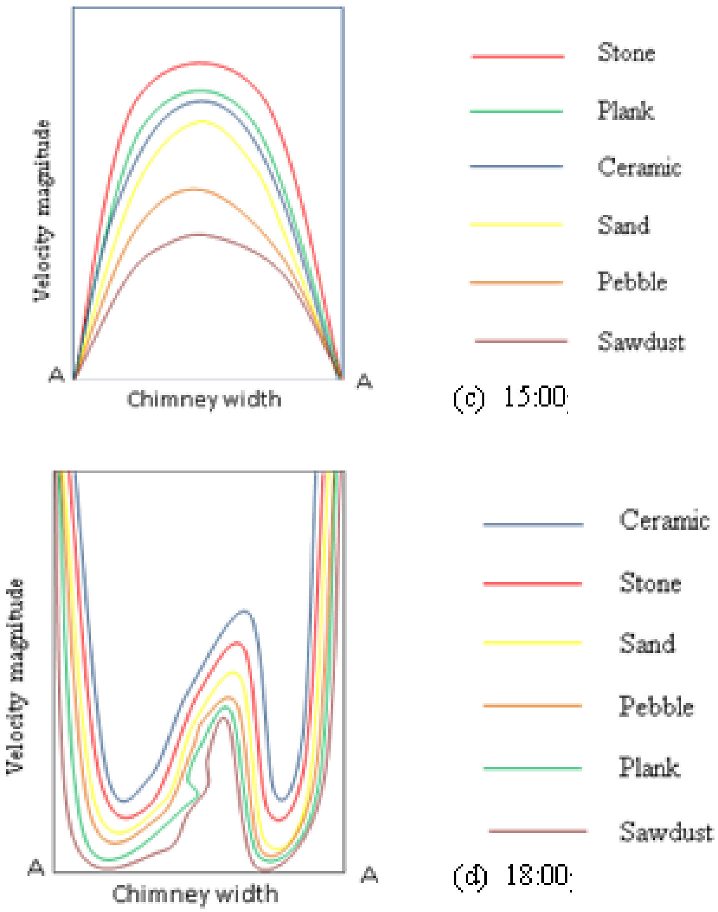

Figure 28 The cross section velocity profile of the test material simulation (3 pm and 6 pm).

The system can be seen behaved similarly in the simulation based on their cross section velocity profile. At 9 am, the velocity profile is not fully developed and began to fully develop at 12 pm. The systems still retain its fully develop velocity profile but at a lower magnitude at 3 pm and then returned to non-fully develop velocity profile at 6 pm.

The behavior of the test ground material can also be seen, the highest performing material differ at each period of simulated time. This is due to their natural characteristic such as thermal storage capacity.

4.3 Related Finding

During the experiment, wind velocity was needed to be measured and recorded at an hourly interval. Upon several days of recording, it was found that the external wind from the environment was affecting the chimney wind velocity. This was suspected since the reading was taken directly after the outlet of the wind using vane type anemometer. Upon discussion, a hot-wire anemometer was later used with holes being drilled at a lower point before the wind outlet. With the adjustment, the same problem insisted. Suspecting the wind on the top outlet may have created a changing pressure zone, a lower point of reading was established only to come up with the same problem. Changing the inlet design to allow a more homogeneous flow of air did not help in solving the problem. Upon further observation and discussion, it is concluded that the source of the problem is due to the effect of the wind form the external environment to interfere with the system in ways both destructive and constructive to the wind velocity inside the chimney. With the wind coming from the rear region of the rig, it will create zones of negative pressure to the atmospheric around the inlet of the collector causing drop in wind velocity reading, and when the wind is blowing from the frontal region of the rig, it will contribute to the increase in the air velocity reading. With the wind flow constantly changing, getting a steady reading of the wind velocity inside the chimney was a challenge on its own.

However based on that behavior, it had given an insight to a betterment of the design of a round collector solar chimney. By introducing slots to the collector base, we were able to harness the kinetic energy of the wind to drive the turbine by channeling it into the chimney. Without slots, the moving wind will only swipe away the heated air in its path. With slots in the collector base, the solar chimney can both benefits the solar radiation energy as well as the ambient wind kinetic energy to drive the turbine.

Illustrated below is the condition occurring during the experiment due to surrounding wind blowing onto the test rig. The wind direction can be divided coming from two directions, the rear of the rig and also the frontal area of the rig.

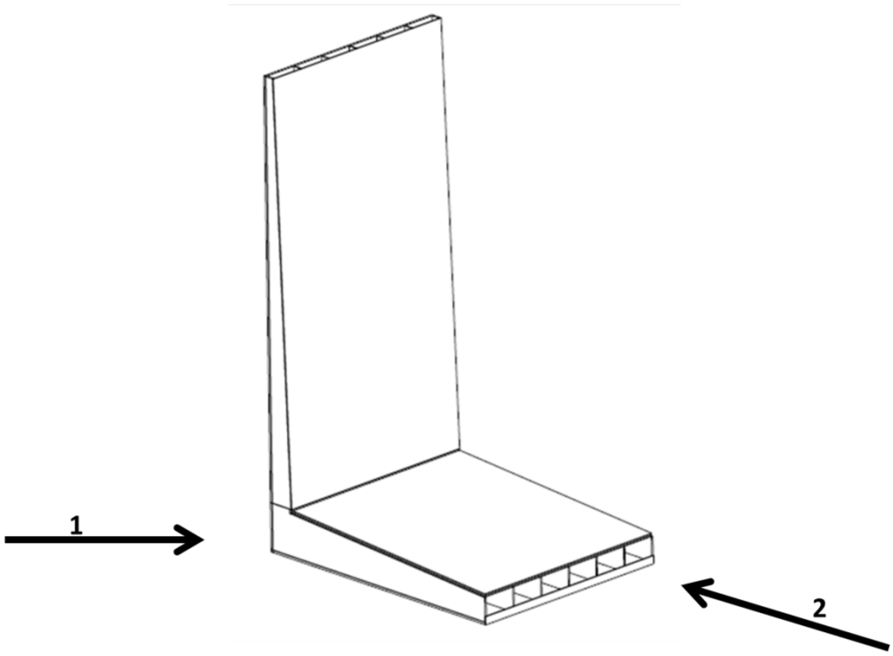

Figure 29 Direction of incoming wind relative to the experimental rig.

If the surrounding wind is blowing from the rear (1) of the rig, it will create a negative pressure zones at the inlet opening while coming from the frontal area (2) of the rig, it will create positive pressure zone at the inlet. The negative pressure will cause drop in air velocity inside the chimney and the positive pressure will boost the air velocity inside the chimney.

This occurrence has given insight to improve the basic design of a round base solar collector. The modification is to introduce separation of the base creating several sectors leading to the chimney. The effect of the modification is shown in the illustration in figure 25.

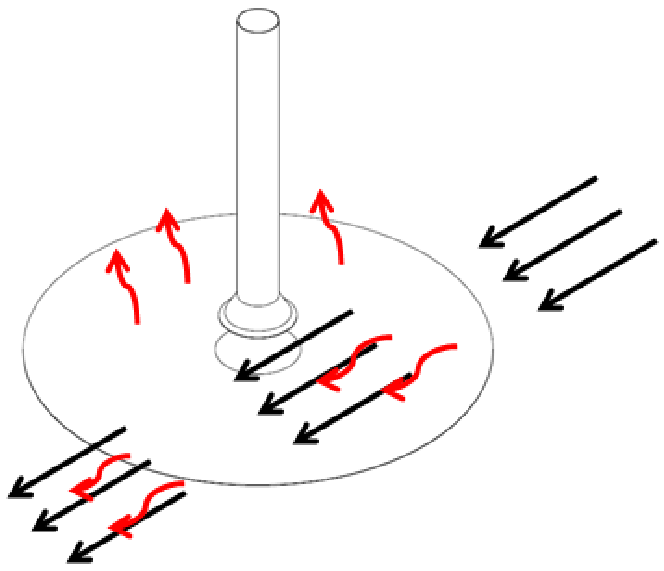

Figure 30 Basic collector design with crosswind flowing.

In this situation, the crosswind blowing inside the collector will sweep the hot air away from the chimney. This will negatively affect the solar chimney overall performance as energy absorbed from the sun's radiation is not being able to drive the turbine. With the solar chimney system being relatively large in scale, isolating the system from the environment is not a viable and feasible option. Modification can be made to make use of the surrounding cross wind.

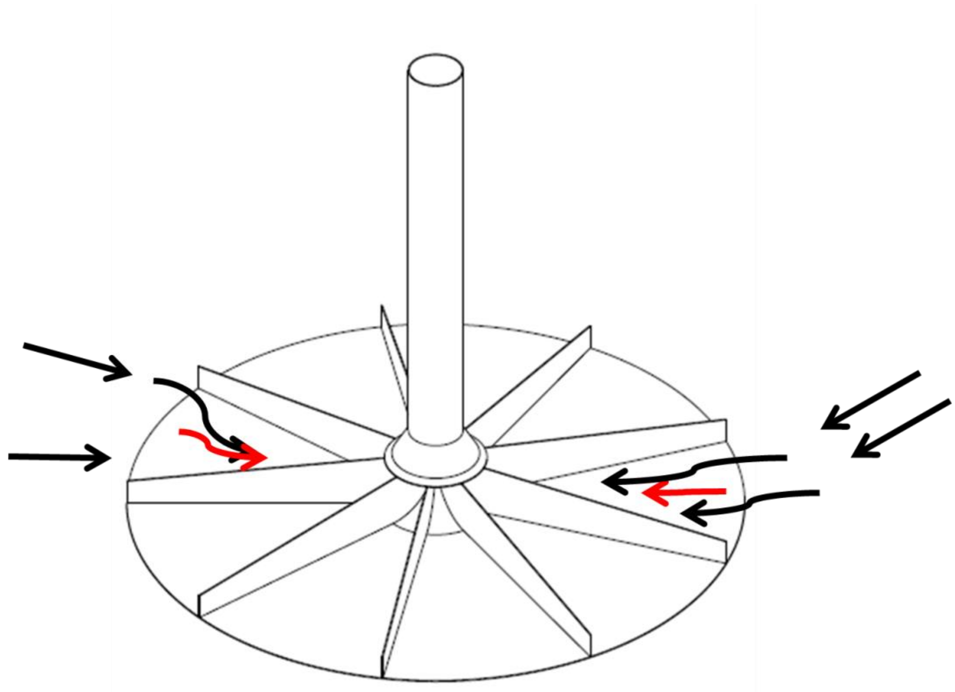

Figure 31 Modification of collector design with crosswind flowing.

With this particular modification, which is dividing the collector into several sectors, we can harness the kinetic energy of the crosswind to boost the air velocity inside the chimney. Air from any direction will be channeled properly into the chimney to increase the performance of the system. Aside from obtaining energy from the solar radiation, wind kinetic energy can also be utilized.

Losses due to crosswind sweeping away hot air are eliminated with improvement to the design and working principle of the solar chimney. Guide vane can be installed at the chimney prior to the turbine to ensure better airflow.

4.4 Conclusion

In conclusion, the experiment was able to differentiate quantitatively the absorptivity characteristic of the ground materials being tested based on their performance to be used in solar chimney applications. The expected results were obtained as well as unintentional result were also founded that could lead to a better design and performance of solar chimney power plant system. The experimental rig could be used to carry different experiment with other configuration to further test the energy generation by the means of utilizing solar radiation. However, the tested ground material can be rank based on their performance (at high radiation range, 200 Watt/m^2 and above) as such:

1. Painted Plywood.
2. Painted Crusher Run (Stone).
3. Painted Ceramics.
4. Painted Pebbles.
5. Saw Dust and Sand are having similar properties with minute variations.

From the efficiency against radiation flux strength graph, it can be conclude that the ceramics poses bigger thermal storage capacity compared to painted plywood as it performs better in lower radiation flux strength due to it being able to release the stored energy at that period of time. Stones is evaluated to be in third place in term of performance, behaving similar to painted plywood but in a lower level of efficiency. Sand, painted pebbles and sawdust performance are relatively similar to each other as ground material of solar chimney collector and being the least suitable candidate as ground material as the experimental data showed. Painted pebbles performance did increases being similar to the performance of ceramics but at the highest radiation readings of the graph. In lower radiation range, its performance is not much difference to the lowest two, the sawdust and sand.

When assessed for the higher value region of the available radiation, the painted plywood is the best followed by painted stones and painted ceramics. In conclusion, the recommended materials to be used as ground materials in SCPP applications are painted plywood, painted stones and painted ceramics. The other three materials which are saw dust, painted pebbles and sand are not recommended as they performed relatively poor compared to the first three.

The experiment also gave an understanding and idea for a new collector design to be evaluated experimentally in the future. Modifications and refinements to the original works can be done to yield better and more precise results. The test rig can be used to preform different solar related experiment at different configuration and small modifications.

This project has achieved its intended objective and also opens opportunity for other discoveries in the future aside from supporting the development of related projects being done at site.

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