# A NEW TYPE OF WIND TURBINE TO SUIT THE SOLAR CHIMNEY FOR POWER PRODUCTION

By

MUHIL PRAKAASH A/L MANICKAM

FINAL PROJECT REPORT

Submitted to the Department of Mechanical Engineering
in Partial Fulfillment of the Requirements
for the Degree
Bachelor of Engineering (Hons)
(Mechanical Engineering)

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# CERTIFICATION OF APPROVAL

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Approved:

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Assoc. Prof. Dr. Hussain H. Al-Kayiem
Project Supervisor

UNIVERSITI TEKNOLOGI PETRONAS
TRONOH, PERAK

May 2012

## CERTIFICATION OF ORIGINALITY

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

______________________________

Muhil Prakaash A/L Manickam

# ABSTRACT


Solar chimney uses the solar thermal energy to heat the air under the solar collector (canopy) which causes difference in density compared to the air outside at ambient temperature. This creates an updraft of air in the chimney. The air updraft created at the base of the chimney would rotate a wind turbine to generate power. This type of power plant requires very large footprint of area and thus research on turbogenerators which operates on very low updraft speed with small footprint of area is necessary.

The objective of this study is to investigate the use of a new type of wind turbine to be used to generate electricity using a small scaled experimental model of solar chimney of 7 m height and 3 m collector diameter. Four separate turbine enclosure cases were studied to investigate the electricity generation. They are the open-ended turbine, the close-ended turbine, cylindrical turbine enclosure and conical turbine enclosure. This is to address the current solar chimney power plant's problem which is the use of conventional wind turbine which requires a minimum of 6 m/s of wind speed to operate.

The scope of the research is the modification of the existing model of solar chimney and the turbine unit. Experimental methods are primarily employed which begins with model design followed by fabrication and testing. For the electricity generation, the unconventional shape of the turbine requires a proper turbogenerator coupling to minimize vibration to the system. Once coupling and enclosures are fabricated, experimentations are performed from 8:00AM – 7:00PM where solar chimney temperature data were recorded hourly and voltage and current readings were recorded every second. The sampling rate of wind velocity, ambient temperature and solar intensity are recorded in 5 minute intervals.

From this research, it has been proven that electricity generation for very small scaled solar chimney using the new type of wind turbine is possible with the best case being the cylindrical turbine enclosure generating a maximum of 2.291W. This is obtained using a rigid turbogenerator coupling.

# ACKNOWLEDGEMENTS

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# CHAPTER 1
# INTRODUCTION

## 1.1 Project Background

Passive cooling plays an important role in providing a thermally suitable environment for human comfort in under-developed countries by providing natural ventilation in dwellings. Solar-induced air ventilation could be provided for by incorporating solar chimneys in buildings. The conventional design of the solar chimney is that it is painted black for high absorptivity and a transparent material for canopy with collectors at the bottom as heat storage medium (Agung & Ahmad, 2007).

Solar chimney has been used for power generation as well by using a wind turbine at the base of the chimney or at the air inlet area. For this research, the solar chimney will be comprised of solar collector, air inlet and outlet area, the vertical tower which act as the chimney and finally the wind turbine under the chimney. Basic operation of the solar chimney is that the sun radiation heats the air inside under the collector. The temperature within the solar collector would then be higher than that of the ambient temperature and causes the difference in air density. This creates buoyancy force which forces the high density air from the outside to push the low density air through the chimney causing natural updraft which then turns the wind turbine at the base of the chimney. A generator then converts the mechanical energy into electrical energy.

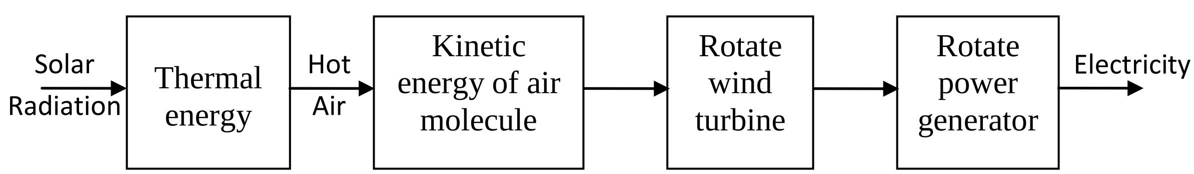



Figure 1.1: Flow scheme of energy conversion within solar chimney (Seow, 2008)

### 1.2 Problem Statement

The solar chimney converts the solar thermal energy to wind which then operates the wind turbine to generate electricity. Traditional wind turbine requires about 6 m/s of wind speed to operate at optimum level. This limitation prompts the construction of huge sized solar chimneys for power generation.

#### 1.2.1 Problem Identification

To operate the wind turbine, 6 m/s of wind speed produced from natural updraft is no easy task. That is why massive scaled solar chimney power plants are built to generate enough buoyancy force to cause a air circulation of 6 m/s. If the power plant is needed to be built by not leaving too much of footprint, the only feasible way is to downsize the model. But this in return causes low wind speed and the conventional wind turbine cannot be used for this application.

#### 1.2.2 Significance of the Project

By implementing the turbine ventilator for the experimental model of solar chimney, evidence can be obtained that electricity can indeed be generated with a very low induced updraft velocity.

### 1.3 Objectives

The objectives of this project are:

a) To investigate experimentally a new type of wind turbine integrated with solar chimney to generate electricity.
b) To investigate the effects on power production with different types of turbine enclosures: open-ended turbine, close-ended turbine, cylindrical turbine enclosure and conical turbine enclosure.

## 1.4 Scope of Study

Modification and improvement work of the existing solar chimney model will be the main focus for the first half of the research. This modification is primarily on the extension of the canopy of the solar chimney. At the same time the study of heat transfer mechanism within the solar chimney will be studied to further understand the operations of the solar chimney model. Methods to implement the wind turbine to generate electricity will also be a focal point. Due to the unconventional wind turbine shape, a proper study on the coupler design is required before fabrication.

## 1.5 Project Relevance

This project is relevant as it will provide results of generated electricity from the proposed turbine ventilator. This turbine has not been used to be tested with the solar chimney before and will provide the required evidence on power generation. This is important as the success of this experimental model may lead to a new design based on the modified turbine ventilator which can be used for a smaller scaled power plant.

## 1.6 Project Feasibility

The project is feasible since it is within the scope and time frame. The author has planned to complete the research and literature review by the end of the first half of the first semester while performing the modification on the solar chimney on the second half of the semester. Author plans to dedicate the second semester to complete the coupler fabrication which will allow power generation. This work however has already been started. The second semester will also witness a few different experiments on power generation using different generators.

# CHAPTER 2
# THEORY & LITERATURE REVIEW

## 2.1 Theory

Solar chimney power plant comprises of three technologies, namely solar air collector, the wind turbine and the chimney. Figure 2.1 shows the different parameters of the power plant.

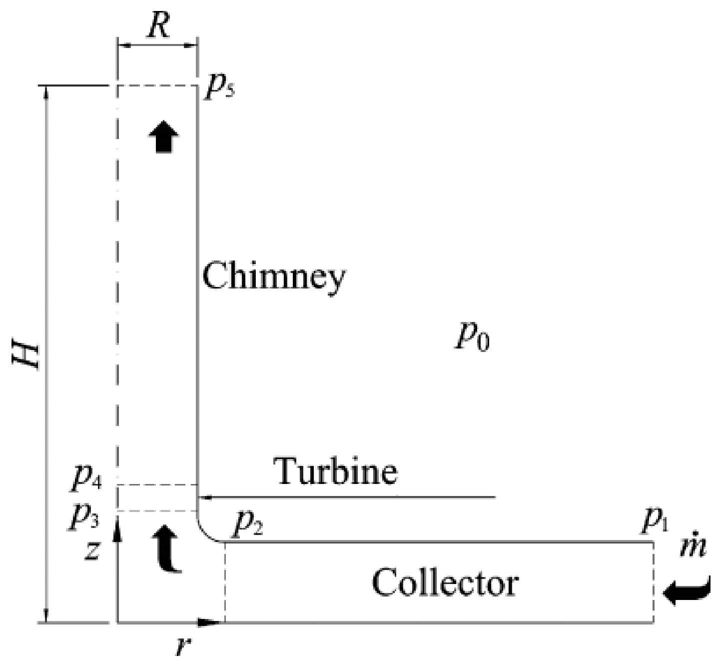



Figure 2.1: Sketch of the flow in a solar chimney (S. Bernades et al., 2003)

Referring to the figure above;

| | | | |
|---|---|---|---|
| $\dot{m}$ | = mass flow rate of air [kg/s] | $p_2$ | = collector outlet pressure [Pa] |
| r | = radius of the solar chimney [m] | $p_3$ | = turbine inlet air pressure [Pa] |
| $p_0$ | = surrounding air pressure [Pa] | $p_4$ | = turbine outlet air pressure [Pa] |
| $p_1$ | = collector inlet air pressure [Pa] | $p_5$ | = chimney outlet air pressure [Pa] |
| $H$ | = height of the chimney [m] | $R$ | = radius of the chimney [m] |

### 2.1.1 Solar Air Collector

For this research, instead of the conventional water tubes, pebbles painted with non-shiny black paint will be used. Figure 2.2 depicts the solar collector's thermal network.

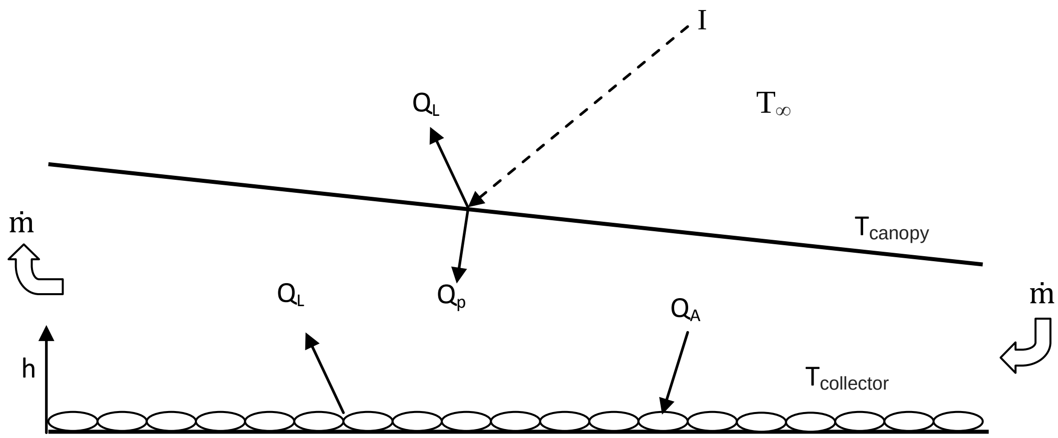
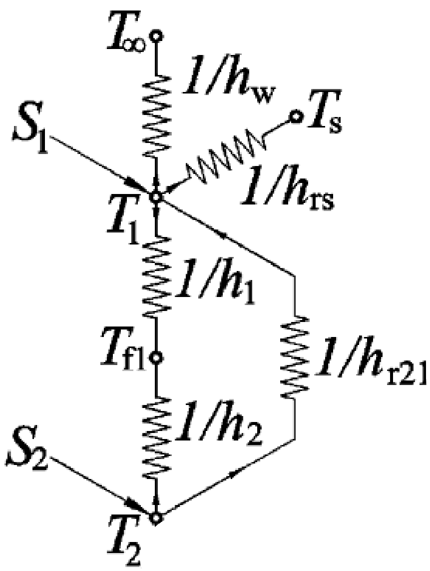



Figure 2.2: Sketch of the Solar Collector's thermal network

Referring to the figure above;

| | | | |
|---|---|---|---|
| I | = Solar radiation [W/m$^2$] | h | = variable height [m] |
| $Q_L$ | = Heat loss from reflection [kJ/kg] | $T_\infty$ | = ambient temperature [$^o$C] |
| $Q_p$ | = Convective heat gain [kJ/kg] | $T_{canopy}$ | = temperature at canopy [$^o$C] |
| $Q_A$ | = Heat absorbed by collector [kJ/kg] | $T_{collector}$ | = temperature at collector [$^o$C] |
| $\dot{m}$ | = air mass flow rate [kg/s] | | |

The solar radiation incident occurs on the Perspex layer of the solar chimney. Here, the sun radiation will be reflected and some will be converted into thermal energy which penetrates the Perspex layer via conduction heat transfer process. Once the Perspex is passed through, the heat will then be transferred via convection into the surrounding air under the collector area. Once the heat travels through the air, some heat will be absorbed by the black pebbles which act as the collector and also some heat will be lost from the pebbles. The heated air will have lower density than the ambient air and this simultaneously causes the induction of a flowing stream of air which pushes the air within the collector from the outside. The hot air will be pushed through the chimney and the process continues.




$h_{r21}$ = $h_{r.g\text{-}c}$
= Radiation heat transfer coefficient

$S_1$ = Total sun radiation

$h_w$ = Convection heat loss by wind from the canopy

$h_{rs}$ = Sky radiation heat transfer coefficient from canopy

$T_\infty$ = Ambient temperature

$T_s$ = Sky temperature ($0.0552T_a^{1.5}$)

$h_1$, $h_2$ = Convective heat transfer coefficient for cover and ground respectively to air

Figure 2.3: Thermal network of solar collector (S. Bernades et al., 2003)

Energy balance at canopy:

$S_1 + h_{r.g\text{-}c}(T_2 - T_1) + h_1(T_{f1} - T_1) = h_w(T_1 - T_a) + h_{rs}(T_1 - T_s)$

Energy balance at ground/collector:

$h_2(T_{f1} - T_2) = h_{r.g\text{-}c}(T_2 - T_1)$

Assumptions made:

i. Air inlet temperature is equal to the ambient temperature.
ii. Air flow is steady.
iii. The Perspex thickness is uniform.
iv. The rib join which holds the Perspex and its extension does not contribute to heat addition.
v. Loss coefficient due to the inclination angle of the canopy is negligible.
vi. Temperature variation is minimal; therefore viscosity and thermal conductivity changes are negligible.
vii. Air density is constant under the canopy until the turbine outlet.
viii. No ground overall heat loss due to insulation.

Governing equations of the system (Incropera et al., 2007):

The convection and radiation heat transfer process can be expressed in form of;

$$q_{convection} = hA(T_s - T_\infty)$$
$$q_{radiation} = \epsilon \sigma A(T_s^4 - T_{\mathrm{sur}}^4)$$

Given,

$T_s$ = Perspex cover temperature

$T_{\mathrm{sur}}$ = Ambient temperature

$T_\infty$ = Air temperature

$h$ = Convection heat transfer coefficient

$A$ = Surface area

$\epsilon$ = Emissivity

σ = Stefan-Boltzman constant (5.67 E-8 $W/m^2.K^4$)

### 2.1.5 Air Stream Mass Flow Rate

From the above figure, ṁ which depicts the air mass flow rate can be calculated using the following equation;

$$\dot{m} = \rho_{air} A V$$

Where,

$\rho_{air}$ = density of air in the system

$A$ = cross sectional area at any point of reference (inlet to outlet)

$V$ = Speed of air flow at any point from inlet to exit of the chimney

Mass flow rate is assumed constant throughout the system and that requires the usage of cross sectional area.

### 2.1.3 Chimney

Chimney provides passage for air to enhance the natural convection process. Due to different density of air at different temperature, there exists different pressure.

Change in pressure, $\Delta p = \rho g H$

Where,

$\rho$ = density of air.

g = gravitational force

H = chimney height

To find the pressure difference produced between the chimney inlet and ambient pressure:

$$\Delta p = g \int_0^{H\ chimney} (\rho_a - \rho_{chimney}) dH$$

The pressure difference can be separated into static and dynamic pressure by assuming that the frictional losses are negligible.

$$\Delta p = \Delta p_{static} + \Delta p_{dynamic}$$

The static pressure difference describes the drop of pressure in at turbine whereas the dynamic pressure describes the kinetic energy of the flow. Assuming the static pressure is zero, the power contained in the flow is now (Toh, 2010):

$$P_{total} = \Delta p . V_{tower\ max} . A_{collector}$$

Utilizing the value of total power in the flow, the efficiency of the tower can be estimated:

$$\eta_{tower} = P_{total} / Q$$

Where,

Q = heat flux

### 2.1.4 Turbine Ventilator

Since a turbine ventilator has almost similar feature with the centrifugal fan, all calculations regarding the turbine will be based on the affinity law. The affinity laws were developed using the law of similitude which provide 3 basic relationships.

Flow vs. diameter and speed

$$\frac{Q}{nD^3}=K \qquad \text{or} \qquad \frac{Q_1}{Q_2}=\frac{n_1}{n_2}\frac{D_1^{\,3}}{D_2^{\,3}}$$

Total Head vs. diameter and speed

$$\frac{g\,H}{n^2\,D^2}=K \qquad \text{or} \qquad \frac{H_1}{H_2}=\frac{n_1^{\,2}}{n_2^{\,2}}\frac{D_1^{\,2}}{D_2^{\,2}}$$

Power vs. diameter and speed

$$\frac{P}{\frac{\gamma}{g}n^3D^5}=K \qquad \text{or} \qquad \frac{P_1}{P_2}=\frac{n_1^{\,3}}{n_2^{\,3}}\frac{D_1^{\,5}}{D_2^{\,5}}$$

Where, subscripts 1 and 2 denote the value of air flow going to the turbine and the air flow properties at the turbine exit. It has to be noted that the turbine ventilator will have a modified exit for the air flow but the value is expected not to differ much and will be tested experimentally.

P is the power, n the speed, D the impeller diameter, H the total head.

If the diameter is fixed the affinity laws become:

$$\frac{Q_1}{Q_2}=\frac{n_1}{n_2} \qquad \frac{H_1}{H_2}=\frac{n_1^{\,2}}{n_2^{\,2}} \qquad \frac{P_1}{P_2}=\frac{n_1^{\,3}}{n_2^{\,3}}$$

### 2.2 Literature Review

The earliest concept and description of solar chimney power station was written by Isidoro Cabanyes in 1903. He made the proposition known as Proyecto de motor solar" (solar engine project) which describes an apparatus with air heater attached to a house chimney with a wind propeller in the house interior for electricity generation (Cabanyes, 1903).

Bernades (2010) discussed about the first development of a prototype solar chimney power plant (SCPP) was done in 1982 in Ciudad Real, 150 km south of Madrid, Spain. With the chimney height of 195 m, diameter of 10 m and collector area of 46,000 $m^2$, it was still considered a small-scaled model and for experimental purposes. Yet, the peak power output was about 50kW which demonstrated and verified the working concept of the plant.

In a study done by Schlaich (1995), few notable advantages of using SCPP were described. Firstly SCPP is able to use both direct and diffuse radiation. Next, the ground provides as natural heat storage. Thirdly, the low number of rotating parts ensures the system's reliability. SCPP's operation also does not require cooling water and simple materials and known technologies are used in its construction. Finally, non OECD countries are able to implement such technology without costly technological effort.

Three essential components of a SCPP are the solar collector, chimney and wind turbine. The solar collector is the glass roof canopy with the natural ground below it. Water filled tubes can be placed under the canopy which will act as the heat storage medium. Solar radiation causes constant updraft where the hot air is continuously sucked into the chimney and cold air enters the collector. By having a pressure staged wind turbine at the base of the chimney, the kinetic energy of the air can be converted into mechanical energy by wind turbine and ultimately into electric energy by the generator. Since the SCPP is highly dependent on the solar radiation, the water tubes under the canopy will release the heat stored at night enabling the SCPP to generate electricity at night as well (Schlaich, 2002).

Gannon & Von Backström (2002a) proposed a turbine design based on the design requirements for a full-scale SCPP integrating the turbine with the chimney. The chimney base legs are radial offset and act as inlet guide vanes introducing pre-whirl before the rotor reducing the exit kinetic energy. The authors stated that the proposed turbine design is able to extract over 80% of the power from the flow. Additionally, a study of a SCPP design was undertaken by Gannon & Von Backström (2002b) and Gannon & Von Backström (2003) where the results of the experimental model turbine revealed a total-to-total efficiency of 85-90% and total-to-static efficiency of 77-80% over the design range.

Fluri & von Backström (2008) have conducted a study which compares the performance of various types of turbogenerator layouts using analytical models and optimization techniques. The turbine layouts which were studied are single rotor and counter rotating turbines, both with or without inlet guide vanes where the single rotor layout without guide vanes was proven to perform very poorly. The efficiency of the other three layouts was showed to be better and lies in a narrow band. The counter rotating layouts provide the highest peak efficiencies, but at relatively low speeds, which leads to an undesirable higher torque for the same power output.

For the case of the variable height solar chimney, Ong & Chow (2003) observed that from an experimental model of 2 m high and 0.45 m diameter canopy with air gaps of 0.1, 0.2 and 0.3 m. Experiments were carried out outdoors on the roof and the experimental model were exposed to direct and diffuse solar radiation. Air velocities between $0.25\ \mathrm{m\ s^{-1}}$ and $0.39\ \mathrm{m\ s^{-1}}$ for radiation intensity up to $650\ \mathrm{W\ m^{-2}}$ were obtained. No reverse air flow circulation was observed even at the large gap of 0.3 m. A different study conducted on the variable height solar chimney of 0.3, 0.4 and 0.45m with chimney heights of 1.6, 2.6 and 3.6 m was conducted by Toh (2010) showed a peak efficiency at canopy height 0.3m and chimney height 3.6m.

The ASHRAE handbook on HVAC applications defines a roof ventilator as a heat escape port located high in a building and properly enclosed for weather tightness with the primary motive forces being stack effects and wind induction. When wind blows on the aerofoil vanes the resulting aerodynamic drag forces cause the turbine ventilator to rotate. This rotation produces a negative pressure inside the turbine ventilator and air is thus sucked from the base duct. Air enters the turbine axially via the base duct and is expelled radially. The experiments conducted by to (N. Khan et al., 2008) proved that a turbine ventilator follows the Affinity Law which is used for centrifugal fans. This is because a turbine ventilator is a combination of a centrifugal fan and an exhaust fan.

According to (N. Khan et al., 2008), the 300 mm curved vane ventilator had about 25% larger flow rate than the 300 mm straight vane ventilator, and 75% larger flow rate than the 250 mm ventilators. The 300 mm curved vane ventilator is lighter in weight. This enables the turbine ventilator to reach a considerably greater rotational speed at all wind speeds, and a greater ventilation capacity.

Fluri et al. (2009) developed an alternative cost model for large-scale solar chimney power plants since the previous economical model were proved to have underestimated the initial capital. The impact of carbon credits on the levelised electricity cost was also investigated.

# CHAPTER 3
# METHODOLOGY

## 3.1 Analysis Technique

The methodologies implemented to incorporate the wind turbine into the variable height solar chimney are:

a) Analytical
b) Model design, testing and fabrication
c) Experimental measurements.

These are primarily important especially in designing and will be discussed further later on.

## 3.2 Research Methodology

The assessment on the efficiency of the turbine ventilator and canopy diameter extension method will be constructed based on several studies and experiment conducted. There are 2 experiments planned to be conducted which are:

- **Experiment 1:** Study and determine the effectiveness of turbine ventilator and the generator used in producing electricity.
- **Experiment 2:** Study on the electricity generation by implementing the turbine at the solar chimney.

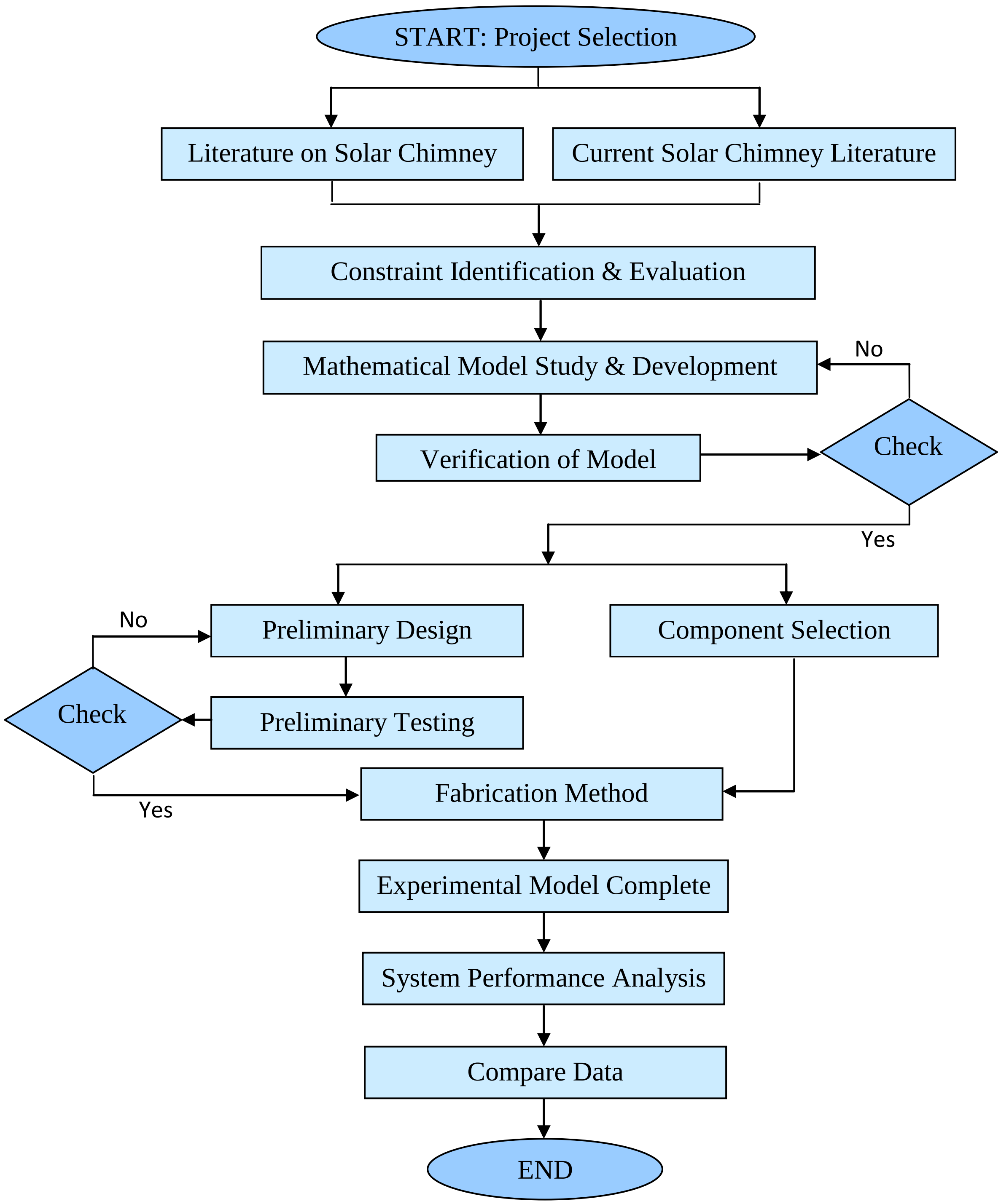
Table 3.1: The Project Activities Flow

| Activities | Description |
|---|---|
| Research and Review Literatures | - Building the research base<br>- Extract relevant parameters and procedures |
| Modification on Solar Chimney Model | - Canopy extension of the existing model by deciding on the method of fabrication.<br>- A few methods were suggested and the most stable design was chosen.<br>- 2 additional height levels were added and chimney height increased to 6 m high. |
| Design and fabrication of the turbogenerator coupler | - Prepare possible configurations for the coupler.<br>- Fabricate the coupler. |
| Testing the effectiveness of the coupler | - Each fabricated coupler will be connected to its generator and turbine.<br>- Induced air stream using external fan will be used to determine if the generator is producing electricity at a similar wind speed of the solar chimney inlet.<br>- Generator used will also be evaluated and changed if needed. |
| Testing with Solar Chimney | - Study the electricity generation using the finalized coupler and generator.<br>- Test will be conducted at lowest canopy height of 0.2m from 8AM - 7PM for 6 days per Case.<br>- Each test will be conducted using four different turbine enclosures.<br>- All related data will be recorded for further analysis. |
| Analyze the Results | - Discuss the findings from the results obtained and make a conclusion out of the study. |
| Report Writing | - Compilation of all works into a final report and technical paper. |

### 3.2.1 Project Flow Chart

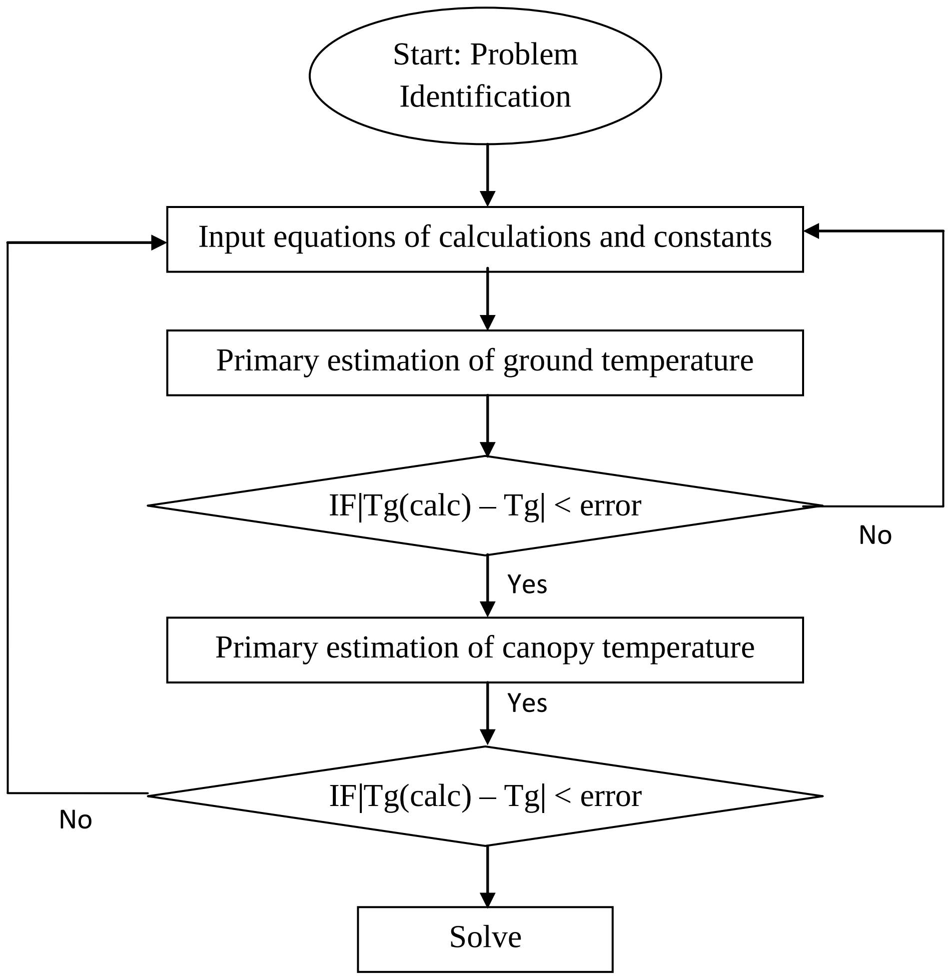
The project execution flow chart has been drafted to show the procedures and steps to be taken throughout the project research period. This flow chart however only covers the current objectives of the research.

Figure 3.2.1: Project Flow Chart



### 3.2.2 Mathematical Model Program Flow Chart

Figure 3.2.2: Mathematical model program flow chart (Toh, J. L., 2010)




Whereby, error <=0.1

$T_{g(calc)}$ = calculated $T_g$ based on the primary estimation of $T_g$

$T_{c(calc)}$ = calculated $T_c$ based on the primary estimation of $T_c$

### 3.3 Extension of the Canopy Diameter

The solar chimney available at the SRS is a very small scaled model compared to the actual power plant. The original diameter was 2.1 m and the objective was to gain a higher buoyancy force from the natural updraft which can be achieved by extending the diameter of the collector area. The first limitation for the extension work is the solar chimney's variable height stand which was fabricated specially for the 2.1 m diameter canopy. The second limitation is that since the canopy is inclined and the material used is Perspex with steel frame, its high mass at the inclined angle will make the extended canopy a fragile and difficult to handle design. It has been suggested that the optimum extension with a stable design would be 3 m in total and so the extension work had been based on a 3 m diameter canopy (Appendix 2), with 0.45 m of extension at each of the 8 faces of the Perspex. The fabrication for the extension was done based on its original model by using L shaped steel support frame to hold the Perspex which will be then sealed using a silicone sealant.

### 3.4 Design and Fabrication of the Turbogenerator Coupler

The coupler design is an ongoing process where so far 2 designs had been discussed and fabricated. After the fabrication of the designs, preliminary testing will be done to evaluate the best design from a mechanics of machine point of view and experiments conducted will provide the data needed to make the final decision. The number of design may be increased or reduced depending on the experimental value of each designs. Another generator may be used to evaluate the electricity generated and the coupler design will be based on the design which will provide the highest rpm and torque for the generator.

### 3.5.1 Gantt Chart & Key Milestone for FYP I

Table 3.5.1: Gantt chart and key milestone for FYP I

| No | Detail/Week | 1 | 2 | 3 | 4 | 5 | 6 | 7 | | 8 | 9 | 10 | 11 | 12 | 13 | 14 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | Project Topic Selection | | | | | | | | Mid-Semester Break | | | | | | | |
| 2 | Research Work & Data Gathering | | | | | | | | | | | | | | | |
| 3 | Mathematical Model Study | | | | | | | | | | | | | | | |
| 4 | Fabrication of canopy diameter extension | | | | | | | | | | | | | | | |
| 5 | Submission of Extended Proposal Defense | | | | | | ✹ | | | | | | | | | |
| 6 | Turbine ventilator implementation design | | | | | | | | | | | | | | | |
| 7 | Proposal Defense | | | | | | | | | | ✹ | | | | | |
| 8 | Submission of Interim Report Final Draft | | | | | | | | | | | | | | ✹ | |

### 3.5.2 Gantt Chart & Key Milestone for FYP II

Table 3.5.2: Gantt chart and key milestone for FYP II

| No | Detail/Week | 1 | 2 | 3 | 4 | 5 | 6 | 7 | | 8 | 9 | 10 | 11 | 12 | 13 | 14 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1. | Research Work | ■ | ■ | ■ | ■ | ■ | ■ | ■ | Mid-Semester Break | ■ | ■ | ■ | ■ | ■ | ■ | ■ |
| 2. | Completion of Collector Area & Chimney Installation | ■ | ■ | ■ | | | | | | | | | | | | |
| 3. | Turbine ventilator Complete Fabrication with Gear Mechanism | | | | ■ | ■ | | | | | | | | | | |
| 4. | Turbine ventilator Complete Fabrication with Centralized Coupler | | | | | | ■ | | | | | | | | | |
| 5. | Experiments on Electricity Generation and Data Gathering/Analysis | | | | | | ■ | ■ | | ■ | ■ | ■ | ■ | ■ | | |
| 6. | Submission of Progress Report | | | | | | | | | ✹ | | | | | | |
| 7. | Pre-SEDEX | | | | | | | | | | | | ✹ | | | |
| 8. | SEDEX & URPC | | | | | | | | | | | | | ✹ | | |
| 9. | Completion of Research Work | | | | | | | | | | | | | ✹ | | |
| 10. | Submission of Dissertation (soft bound) | | | | | | | | | | | | | | ✹ | |
| 11. | Submission of Technical Paper | | | | | | | | | | | | | | ✹ | |
| 12. | Oral Presentation | | | | | | | | | | | | | | | ✹ |
| 13. | Submission of Dissertation (Hard bound) | | | | | | | | | | | | | | | ✹ |

## 3.6 Tools and Software Required

In this section, the materials needed to construct the extension of the canopy will be listed and then the tools and software needed for the experiments using the solar chimney will be listed separately.

### 3.6.1 Material for Extension Construction

- L-Shaped steel bar
- Perspex
- Silicone sealant

### 3.6.2 Tools for Experiments

- Variable height Solar Chimney
- Turbine Ventilator
- DC Motor/Generator
- Multimeter
- Solar Meter
- Portable hot wire anemometer
- Thermocouple probes
- Data Logger

### 3.6.3 Software for Design/Modeling/Documentation

- Microsoft Office Excel
- Microsoft Office Word

# CHAPTER 4
# RESULT & DISCUSSION

## 4.1 Prototype/Experimental Model of Solar Chimney

The previous work on the Solar Chimney model was left at 2.1m diameter of canopy. The chimney meanwhile consisted of 0.6m (6” diameter) at the base and connected with 1m, 2m or 3m long chimneys of 6” diameter or can be reduced to a 4” diameter chimney. The current work however focuses on maximizing the natural updraft effect. So, only a single chimney has been used with 6” diameter and 6m long from the inlet. The use of 4” diameter and 6m long chimney with reducer will be used for the future research work. Below are the flowchart representations of the previous and current work.

Figure 4.1.1: Flowchart of previous solar chimney model.

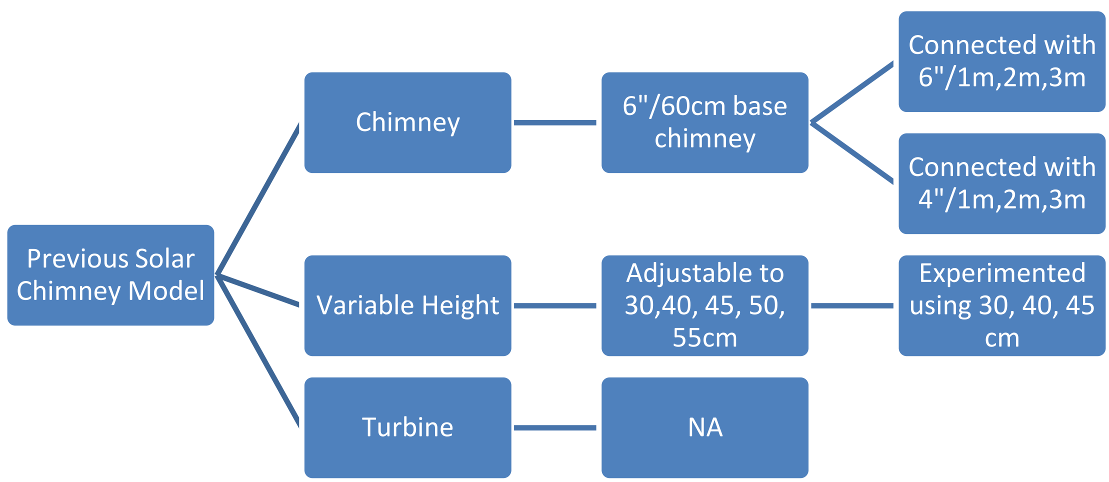


Figure 4.1.2: Flowchart of current solar chimney model.

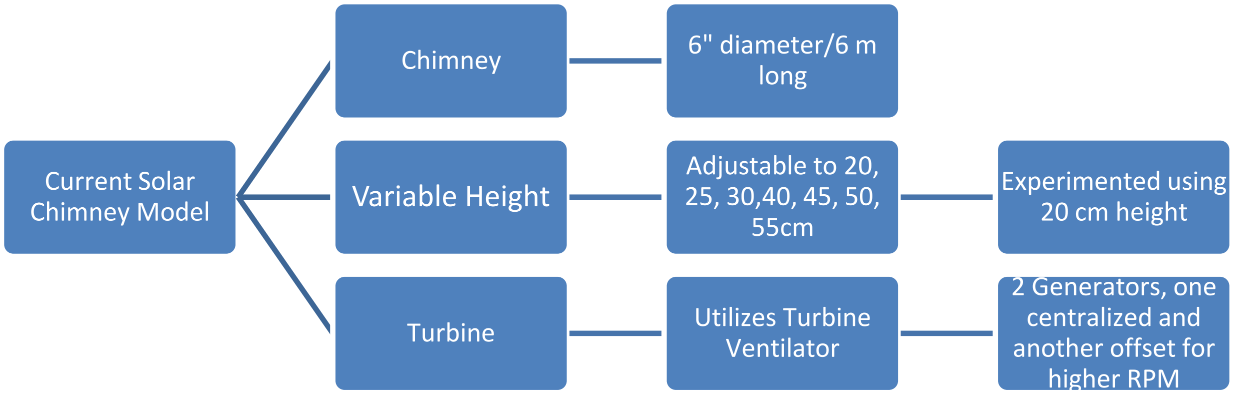
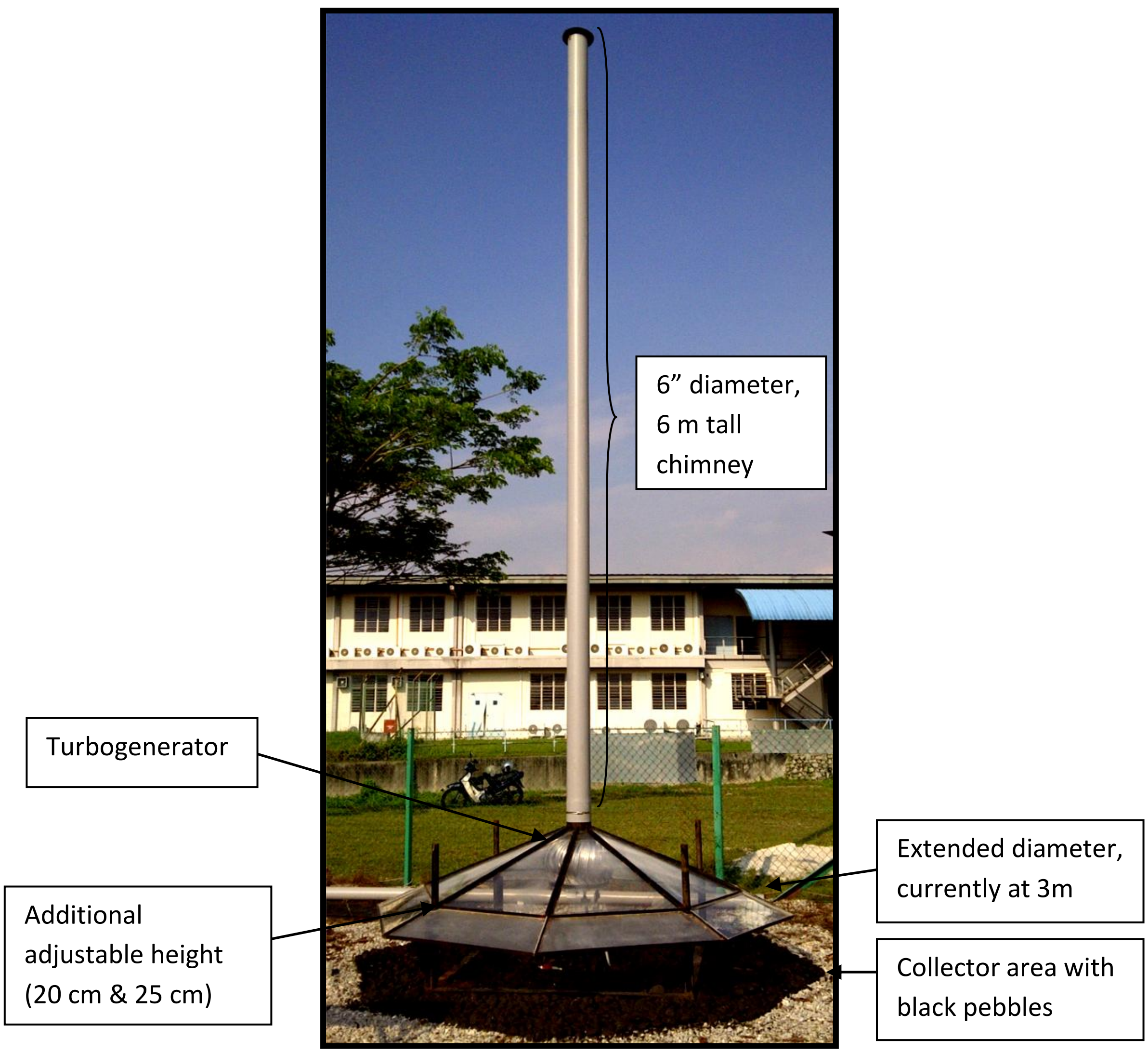



Figure 4.1.3: Completed Solar Chimney Model



## 4.2 Prototype/Experimental Model of Turbogenerator

Few things to be noted about the turbine ventilator and generator are as the followings:

a) Swaying rotation

   The design of the industry manufactured turbine ventilator has mechanical flaws and one which is the most difficult to deal with is the swaying rotation. In one revolution, the turbine has lateral and vertical motions. This poses a challenge in designing a coupling for the generator which can handle this motion.

b) Very low rotational torque

   Due to its large shape being supported in the middle to provide least amount of force on its joints, turbine ventilator has a very low rotational torque. So, even a slight contact of the coupler may stop the turbine rotation.

c) DC Motor used as a generator

   12V DC motor is used as a generator to produce electricity since it has a very low start up torque for rotation.

Two separate mechanisms had been installed to the Turbogenerator. They are:

a) Rigid coupler

   Provides equal RPM to the generator and no additional forces are acted on the turbine ventilator. Low amount of electricity can be produced (5-3000 mV). Since the swaying rotation causes the generator to sway along, silicone sealant tape is used to mount the generator at chimney inlet. The elasticity of the sealant allows slight movement and protects the Perspex mount from stresses.

b) Flexible Coupler

   A spur gear mechanism has been fabricated for the turbine. The gear radius of the generator gear is fabricated to 1" and the radius of the turbine base is 6". This provides the generator shaft 6 times the RPM of each Turbine revolution. Much larger amount of electricity can be produced (1-7 V). But due to the gear contact between the turbine and generator, much larger natural updraft is needed for the turbine to rotate. To accommodate for the swaying rotation of the turbine, the generator is mounted on a hinged suspension which allows the 'tracking' of the turbine motion with zero slips.

Figure 4.2.1: Initial rigid coupling Turbogenerator (L: Top view, R: Side View)

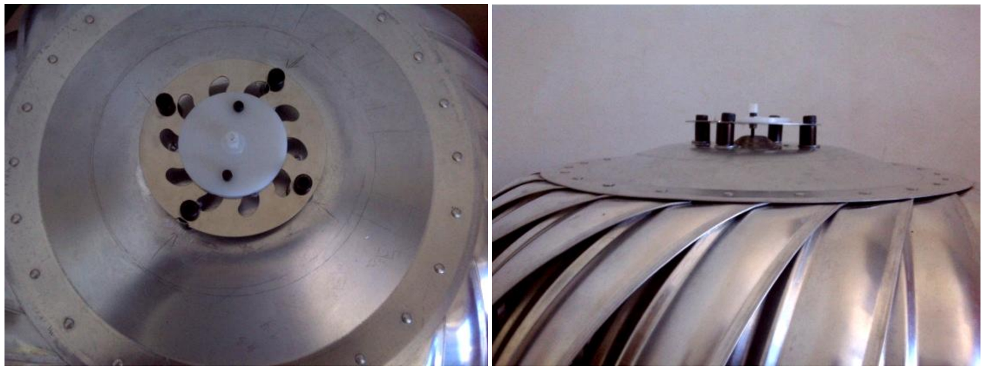


Figure 4.2.2: Current rigid coupling for Turbogenerator Prototype

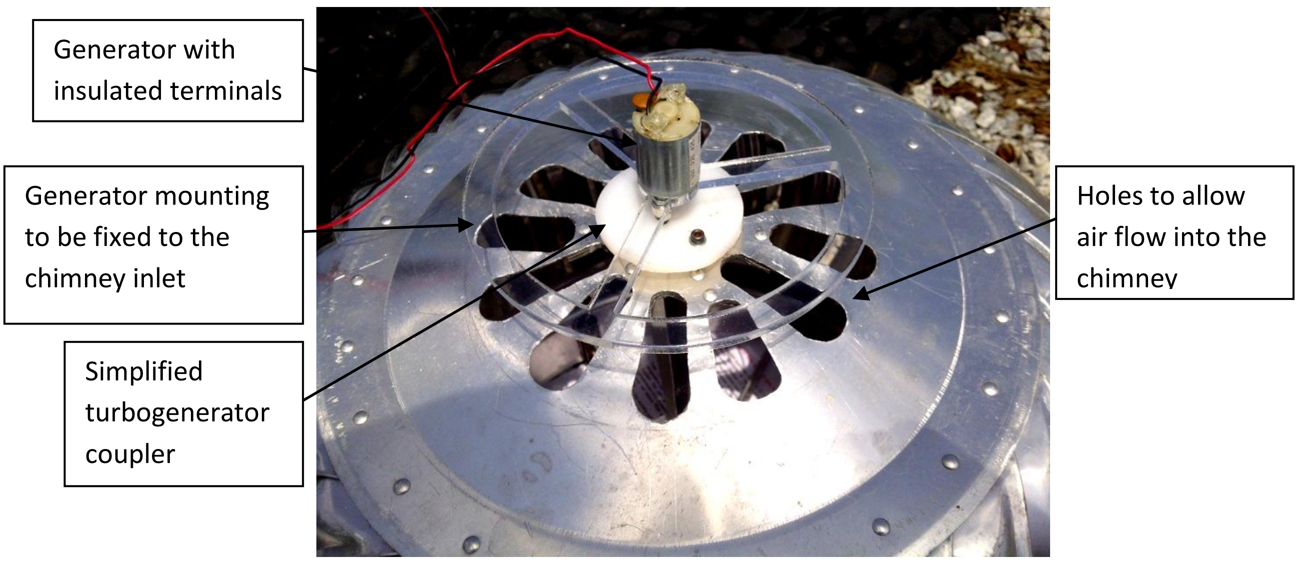



Figure 4.2.3: Current Inline Turbogenerator Prototype Fixed in Solar Chimney

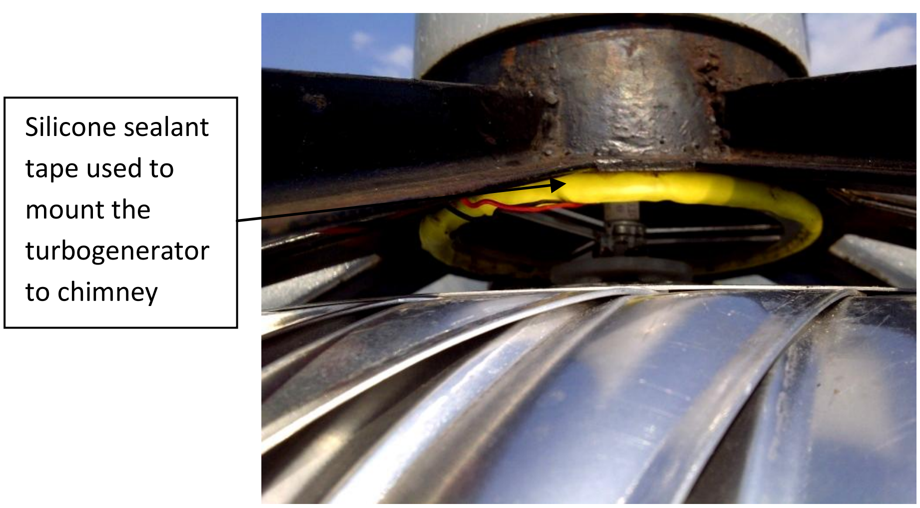


Figure 4.2.4: Flexible Turbogenerator coupling (Side view)

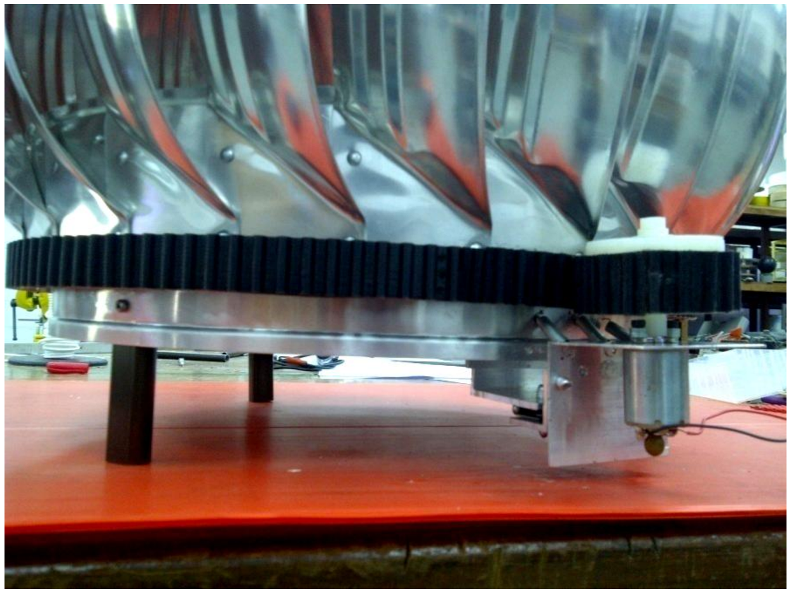


Figure 4.2.5: Flexible Turbogenerator coupling (Bottom view)

Figure 4.2.6: Turbogenerator Tripod leg (Bottom view: Folded Tripod)

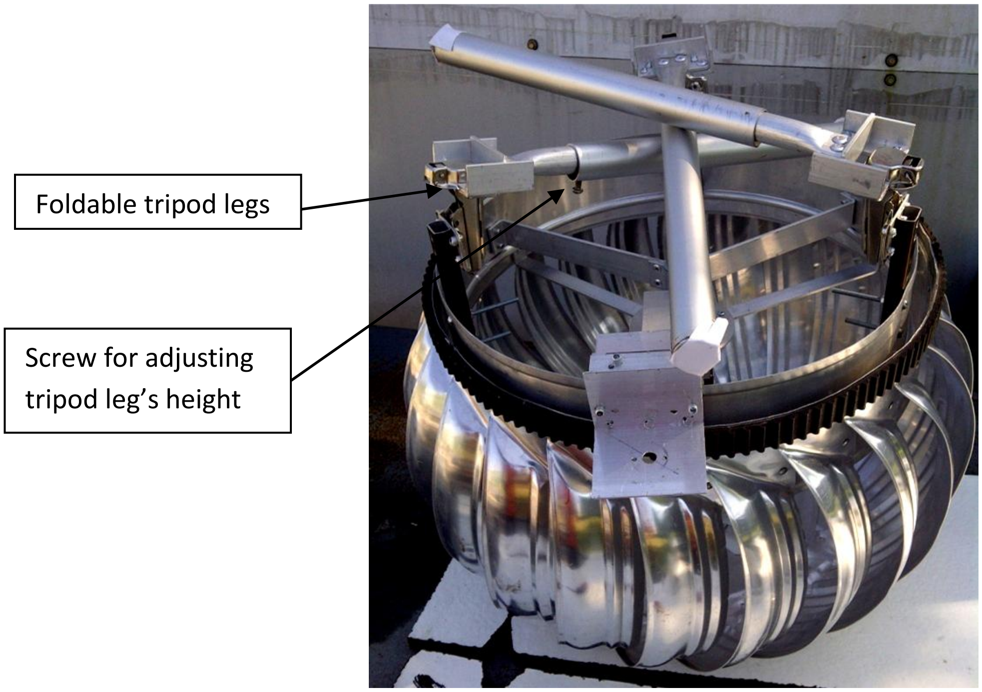



Figure 4.2.7: Turbogenerator Prototype (Front view: With Tripod stand)

Figure 4.2.8: Turbine with cylindrical enclosure for Case 3

Figure 4.2.9: Turbine with conical enclosure for Case 4

## 4.3 Data Gathering

This section contains the sample data collected for all four cases. For Case 3 and Case 4, the best yielded result experimentation data will be shown.

Table 4.3.1: Case 1 Data recorded

| Time | T amb (°C) | Tf (°C) | Tc (°C) | Tg (°C) | Vw (m/s) | Is (W/m2) |
|---|---|---|---|---|---|---|
| 8:00 AM | 25.54 | 26.5 | 26.89 | 26.72 | 1.12 | 136.16 |
| 9:00 AM | 27.41 | 29.43 | 29.172 | 30.65 | 0.98 | 335.4 |
| 10:00 AM | 29.7 | 32.043 | 36.89 | 37.58 | 0.57 | 548.74 |
| 11:00 AM | 30.69 | 36.9 | 40.04 | 44.125 | 1.8 | 776.63 |
| 12:00 PM | 31.83 | 40.2 | 42.15 | 46.05 | 1.64 | 710.93 |
| 1:00 PM | 32.55 | 40.94 | 46.25 | 49.525 | 1.63 | 857.81 |
| 2:00 PM | 33.48 | 41.67 | 47.3 | 50.95 | 1.03 | 859.91 |
| 3:00 PM | 31.99 | 40.18 | 47.15 | 50.43 | 1.45 | 633.6 |
| 4:00 PM | 29.64 | 37.21 | 40.525 | 47.94 | 0.58 | 409.5 |
| 5:00 PM | 28.49 | 36.74 | 36.175 | 43.35 | 1.45 | 369.64 |
| 6:00 PM | 27.34 | 35.525 | 35.645 | 38.02 | 2.01 | 134.06 |
| 7:00 PM | 26.77 | 31.23 | 32.125 | 34.075 | 0.53 | 9.4 |

Table 4.3.2: Case 2 Data recorded

| Time | T amb (°C) | Tf (°C) | Tc (°C) | Tg (°C) | Vw (m/s) | Is (W/m2) |
|---|---|---|---|---|---|---|
| 8:00 AM | 24.93 | 28.45 | 28.58 | 28.53 | 1.41 | 127.04 |
| 9:00 AM | 27.74 | 29.73 | 29.68 | 30.43 | 1.13 | 335.18 |
| 10:00 AM | 30.43 | 33.53 | 37.90 | 38.08 | 1.23 | 567.68 |
| 11:00 AM | 28.76 | 36.23 | 41.13 | 45.00 | 2.98 | 784.35 |
| 12:00 PM | 31.9 | 39.05 | 43.78 | 46.08 | 3.1 | 806.48 |
| 1:00 PM | 31.99 | 39.20 | 48.05 | 50.25 | 3.11 | 806.48 |
| 2:00 PM | 32.24 | 41.58 | 48.18 | 52.48 | 3.5 | 906.68 |
| 3:00 PM | 32.36 | 40.88 | 47.18 | 51.90 | 2.52 | 756.82 |
| 4:00 PM | 31.58 | 37.75 | 40.90 | 47.30 | 2.73 | 327.95 |
| 5:00 PM | 32.11 | 35.53 | 37.58 | 44.30 | 2.46 | 343.72 |
| 6:00 PM | 29.35 | 35.38 | 37.05 | 41.40 | 1.26 | 125.03 |
| 7:00 PM | 29.35 | 31.23 | 32.58 | 34.75 | 0.01 | 8.32 |

Table 4.3.3: Case 3 Data recorded

| Time | T amb (°C) | Tf (°C) | Tc (°C) | Tg (°C) | Vw (m/s) | I s (W/m2) |
|---|---|---|---|---|---|---|
| 8:00 AM | 25.54 | 27.70 | 27.55 | 28.88 | 1.12 | 136.16 |
| 9:00 AM | 27.41 | 28.05 | 28.33 | 29.18 | 0.98 | 335.40 |
| 10:00 AM | 29.70 | 31.95 | 31.93 | 33.28 | 0.57 | 548.74 |
| 11:00 AM | 30.69 | 37.50 | 38.43 | 41.65 | 1.80 | 776.63 |
| 12:00 PM | 31.83 | 40.60 | 41.93 | 49.80 | 1.64 | 710.93 |
| 1:00 PM | 32.55 | 40.13 | 41.05 | 50.83 | 1.63 | 857.81 |
| 2:00 PM | 33.48 | 39.28 | 41.45 | 45.90 | 1.03 | 859.91 |
| 3:00 PM | 31.99 | 41.33 | 40.23 | 44.60 | 1.45 | 633.60 |
| 4:00 PM | 29.64 | 39.00 | 37.83 | 41.88 | 0.58 | 409.50 |
| 5:00 PM | 28.49 | 37.43 | 38.48 | 41.33 | 1.45 | 369.64 |
| 6:00 PM | 27.34 | 35.68 | 37.00 | 39.98 | 2.01 | 134.06 |
| 7:00 PM | 26.77 | 32.50 | 33.53 | 35.08 | 0.53 | 9.40 |

Table 4.3.4: Case 3 Data recorded on power produced

| Time | Duration (s) | Voltage (V) | Current (A) | P (W) |
|---|---|---|---|---|
| 11:45 AM | 6 | 1.03 | 0.0179 | 0.018 |
| 11:57 AM | 11 | 1.5 | 0.2 | 0.300 |
| 12:05 PM | 8 | 1.8 | 0.13 | 0.234 |
| 12:08 PM | 7 | 2.8 | 0.22 | 0.616 |
| 12:19 PM | 16 | 3.1 | 0.56 | 1.736 |
| 12:21 PM | 12 | 2.4 | 0.6 | 1.440 |
| 12:24 PM | 10 | 2.8 | 0.46 | 1.288 |
| 12:26 PM | 7 | 1.7 | 0.43 | 0.731 |
| 12:39 PM | 5 | 1.2 | 0.19 | 0.228 |
| 12:41 PM | 26 | 3.58 | 0.64 | 2.291 |
| 12:47 PM | 8 | 1.9 | 0.37 | 0.703 |
| 1:02 PM | 4 | 2.4 | 0.35 | 0.840 |
| 1:21 PM | 3 | 1.3 | 0.14 | 0.182 |
| 1:36 PM | 21 | 3.2 | 0.65 | 2.080 |

From Table 4.3.4, high current output was recorded with the maximum of 0.65 A. This high current will allow the use Operational Amplifiers to be used to step up the Voltage up to 5V-10V. But to utilize the means of stepping up the voltage, a constant power production must first be achieved.

Table 4.3.5: Case 4 Data recorded

| Time | T amb (°C) | Tf (°C) | Tc (°C) | Tg (°C) | Vw (m/s) | I s (W/m2) |
|---|---|---|---|---|---|---|
| 8:00 AM | 24.9 | 27.55 | 26.375 | 26.925 | 0.2 | 133.24 |
| 9:00 AM | 27.71 | 27.75 | 28.1 | 28.725 | 0.43 | 321.71 |
| 10:00 AM | 29.51 | 32.35 | 34.4 | 33.125 | 1.4 | 535.54 |
| 11:00 AM | 31.53 | 34.825 | 38.75 | 44.325 | 3.68 | 690.49 |
| 12:00 PM | 31.53 | 39.475 | 42.05 | 47.025 | 3.43 | 907.54 |
| 1:00 PM | 32.19 | 41.2 | 44.025 | 48.15 | 2.81 | 840.56 |
| 2:00 PM | 32.58 | 39.8 | 42.5 | 44 | 3.14 | 777.19 |
| 3:00 PM | 32.12 | 41.25 | 43.075 | 46.125 | 2.14 | 623.33 |
| 4:00 PM | 31.54 | 40.2 | 41.1 | 44.4 | 1.28 | 349.54 |
| 5:00 PM | 31.76 | 37.95 | 41.55 | 42.65 | 1.37 | 312.32 |
| 6:00 PM | 29.43 | 34.95 | 37.45 | 39.425 | 2.1 | 113.49 |
| 7:00 PM | 29.41 | 32.25 | 33.3 | 36.2 | 0.63 | 10.86 |

Table 4.3.6: Case 4 Data recorded on power produced

| Time | Duration (s) | Voltage (V) | Current (A) | Power (W) |
|---|---|---|---|---|
| 11:31 AM | 2 | 0.85 | 0.15 | 0.128 |
| 12:01 PM | 3 | 0.1 | 0.14 | 0.140 |
| 12:15 PM | 6 | 0.64 | 0.12 | 0.008 |
| 12:17 PM | 8 | 0.2 | 0.45 | 0.900 |
| 12:18 PM | 10 | 2.7 | 0.26 | 0.702 |
| 12:57 PM | 5 | 0.78 | 0.2 | 0.156 |

Table 2 shows low power output value with much lower frequency compared to Case 3. By comparison to Table 1, the duration of the power generation is also low for Case 4 as Case 3 recorded the longest continuous power generation of 26 seconds.

## 4.4 Data Analysis

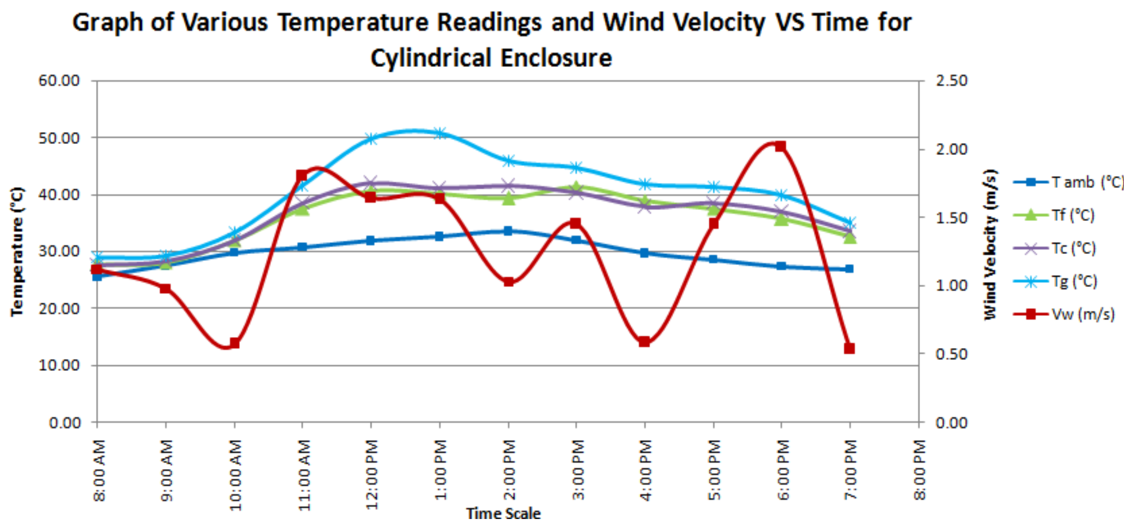



Figure 4.4.1: Graph of temperature profiles and wind velocity versus time for Case 3

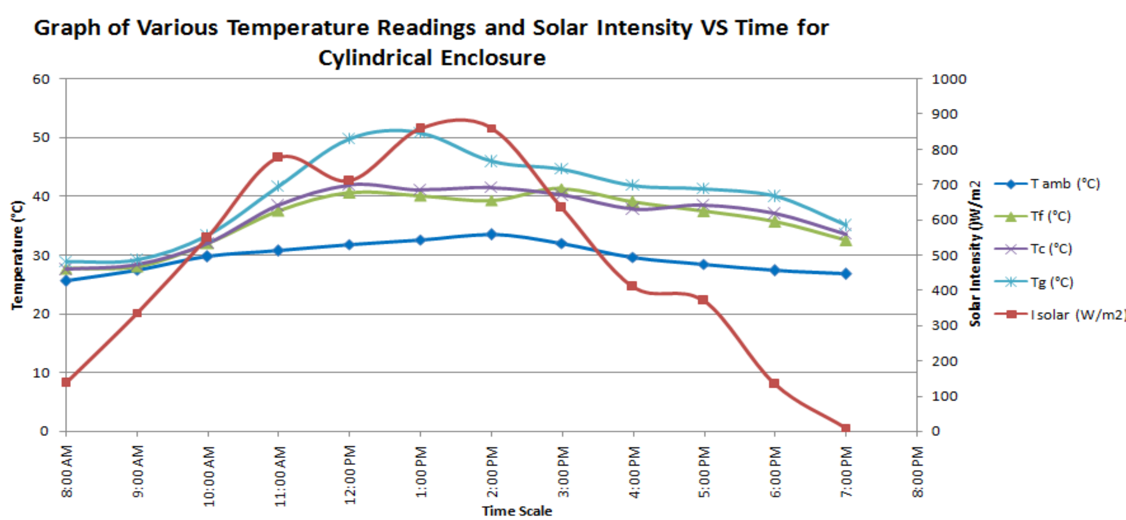



Figure 4.4.2: Graph of temperature profiles and Solar Intensity versus time for Case 3

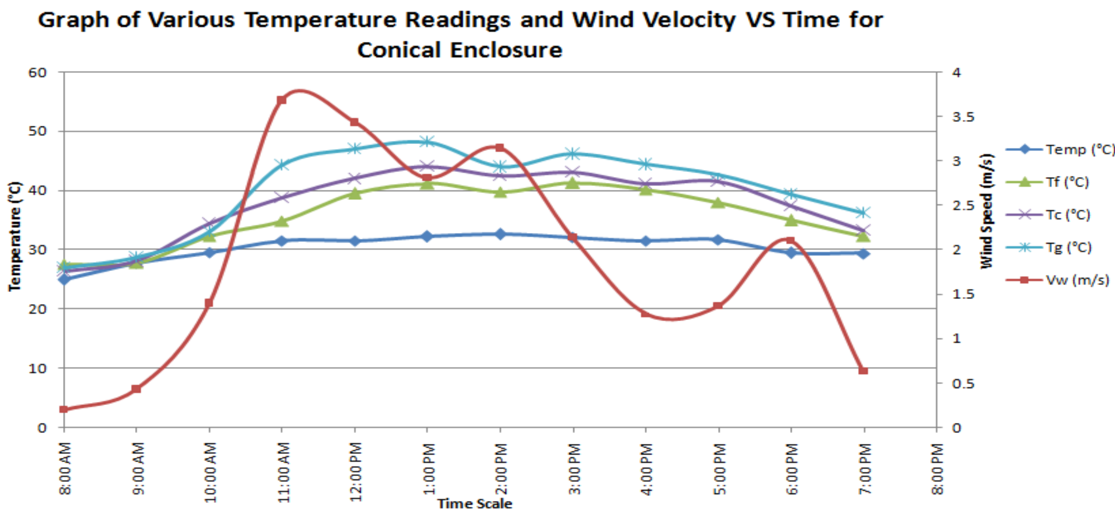



Figure 4.4.3: Graph of temperature profiles and wind velocity versus time for Case 4

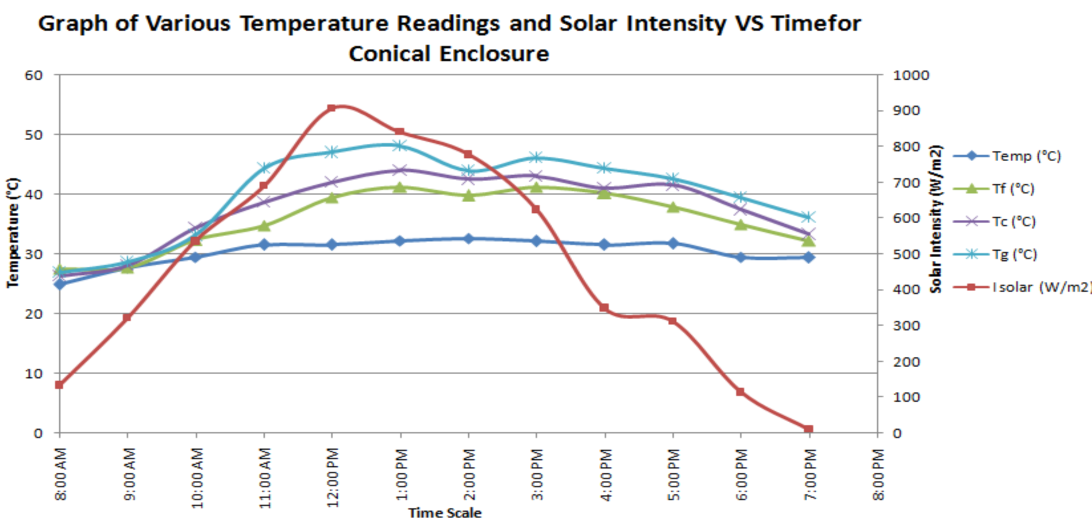



Figure 4.4.4: Graph of temperature profiles and Solar Intensity versus time for Case 4

<u>Case 1: Open-ended turbine</u>

No electricity was generated for this case as the turbine did not rotate. This is because with this configuration, the natural updraft can easily enter the 14” diameter turbine inlet and exit through the slots on top into the chimney. With open-ended turbine, the natural updraft and the wind will have cross-flows under the turbine which may cause very little natural updraft from occurring. The weather condition during experimentation was similar to the other cases.

Case 2: Close-ended turbine

Electricity was not generated for this case as well. On occasion, there was slight rotation of the turbine but not enough to produce any electricity. A closed-end turbine may block the air from entering through the middle but the cross-flow of wind and natural updraft is still a problem to be addressed.

Case 3: Cylindrical turbine enclosure

Electricity was generated for this case and was recorded to be the highest at 2.29 W at 12:41 PM as shown in Figure 10 . Figure 11 below shows clearly that from 11:30 AM to 1:00 PM, not only is the high solar intensity contributes to the high solar chimney temperature, but at that time period the wind velocity is also an average high. From Figure 10, it can be seen from the temperature profiles that the maximum difference in temperature between the ambient and the temperature inside the collector is 8.77 $^{o}$C at 12:00 PM.

Case 4: Conical turbine enclosure

Electricity was generated but at a much lower rate and frequency than the cylindrical enclosure. The peak power output of 0.9W was recorded at 12:17 PM. From Figure 12 and 13, it can be seen that the solar intensity was recorded highest at 12:00 AM followed by a gradual drop. The wind velocity reached its peak (3.68 m/s) at 11:00 AM but started to drop during the peak sun hour from 12:00 PM till 4:00 PM. From Figure 12, it can be seen from the temperature profiles that the maximum difference in temperature between the ambient and the temperature inside the collector is 9.13 $^{o}$C at 3:00 PM followed by 9.01 $^{o}$C at 1:00 PM.

Analysis on power production

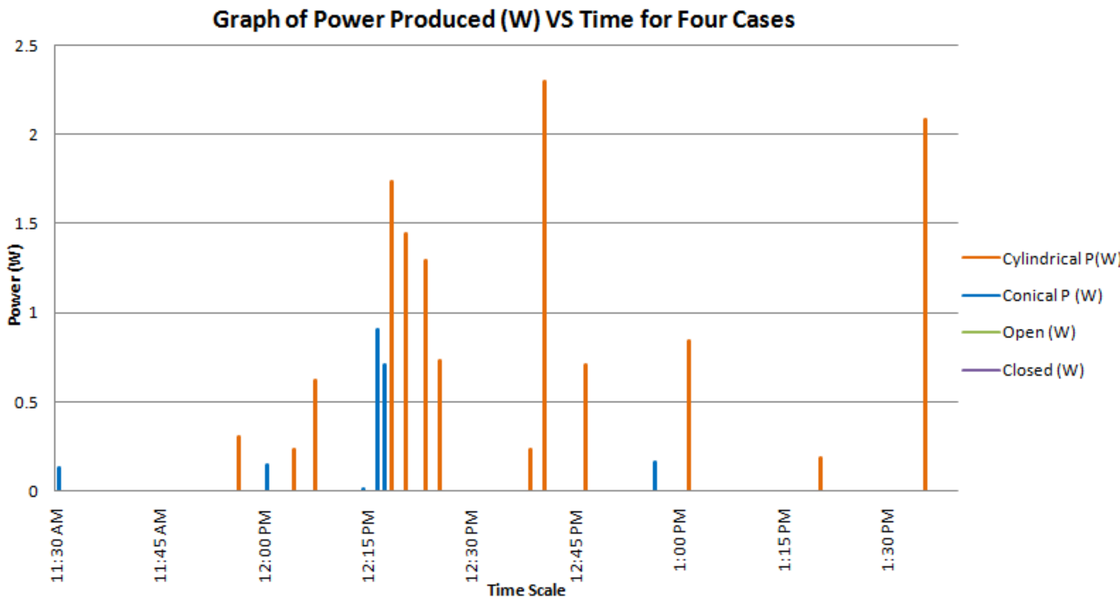



Figure 4.4.5: Graph of power produced versus time for all four cases.

The Case 3 with cylindrical enclosure recorded the highest power output and also with the highest frequency of electricity generation where power above 1W was produced 5 times from 12:19 PM to 1:36 PM. During this period, the solar intensity was high and the ground temperature had reached 50 $^{o}$C along with the high temperature difference between the ambient and the solar collector. The comparisons of the results are shown in Figure 4.4.5.

It was observed from the experiments that the turbine rotate at a certain intervals throughout the test period for the rigid coupling mechanism. Meanwhile, the turbine only rotated twice for a period of 10s for the flexible coupling (spur gear) mechanism. Since the operation of the solar chimney needs the air to be heated up under the collector, it is logical that the turbine would have an ‘interval of rotation’ to allow for the next batch of heating the air. This will be due to the very small scaled experimental model. The spur gear mechanism has force acting on the turbine and so it would only rotate at wind speed higher than 3.5m/s which was tested using induced external air stream during the preliminary testing for the coupling mechanism selection.

Power forecast using Affinity Law derivative

$$\frac{P_1}{P_2} = \left(\frac{D_1}{D_2}\right)^{-4} \left(\frac{Q_1}{Q_2}\right)^{3}$$

Table 4.4: The theoretical power prediction using Affinity Law

| **FYP SCPP Model** | | **Manzanares SCPP** | |
|---|---|---|---|
| **$V_1$** | 2.2 m/s | $V_2$ | 15 m/s |
| **$Q_1 = V_1 \times A_1$** | 0.39 $m^3/s$ | $Q_2 = V_2 \times A_2$ | 294.5 $m^3/s$ |
| **$D_1$** | 0.475 m | $D_2$ | 5 m |
| **$P_1$** | 1.767 W | **$P_2$** | **61, 973.05 W** |

$P_2$ is the theoretical power produced based on the data from the Solar Chimney in Manzanares using the modified turbine ventilator with dimensions scaled to suit the Manzanares SCPP. The original Manzanares SCPP generated 50kW of power. By using the new type of wind turbine, 61.97kW may be produced, an increase of 19.3%. The power $P_1$ is an average stable power produced above 1W by the Case 3 experiment.

This forecast of power for a modified turbine ventilator may not be very accurate. Therefore, to have an accurate forecast model, more research has to be done on small scale solar chimney with the turbine modified to suit the size of the chimney.

# RECOMMENDATIONS & CONCLUSION

## 5.1 Recommendations

It is recommended to have a more detailed study to be done with longer experimentation period to observe if the Case 4 with conical enclosure can generate higher electricity. This is primarily due to the aerodynamic design of the enclosure which might allow an even more efficient air flow. This configuration however covers more area and therefore decreases the solar collector area.

Besides that, it is recommended to improve the experimental setup by utilizing a DC Voltage and Current data logger with the highest sampling rate available. Flue gas can also be used to increase the temperature difference between the ambient and the solar collector.

The solar collector diameter should also be expanded to at least 10 m with a higher chimney and investigate the performance of the turbine for power production. The turbine however has to be scaled up so that the results can be compared with this research and obtain a mathematical model which can be used for power production forecasting.

## 5.2 Conclusion

In conclusion, it is proven that the modified turbine ventilator enables electricity generation for a small-scaled solar chimney with low natural updraft. Furthermore, the investigation concludes that the cylindrical enclosure is the best turbine base to be used to prevent cross-flow of air and also to increase the turbine rotation.

The solar chimney modification also plays a vital role on the power production as it increases the natural updraft velocity which in return allows turbine rotation for power production. The mechanism used for turbogenerator has a negligible start up torque which allows the turbine to operate without additional forces acting on it.

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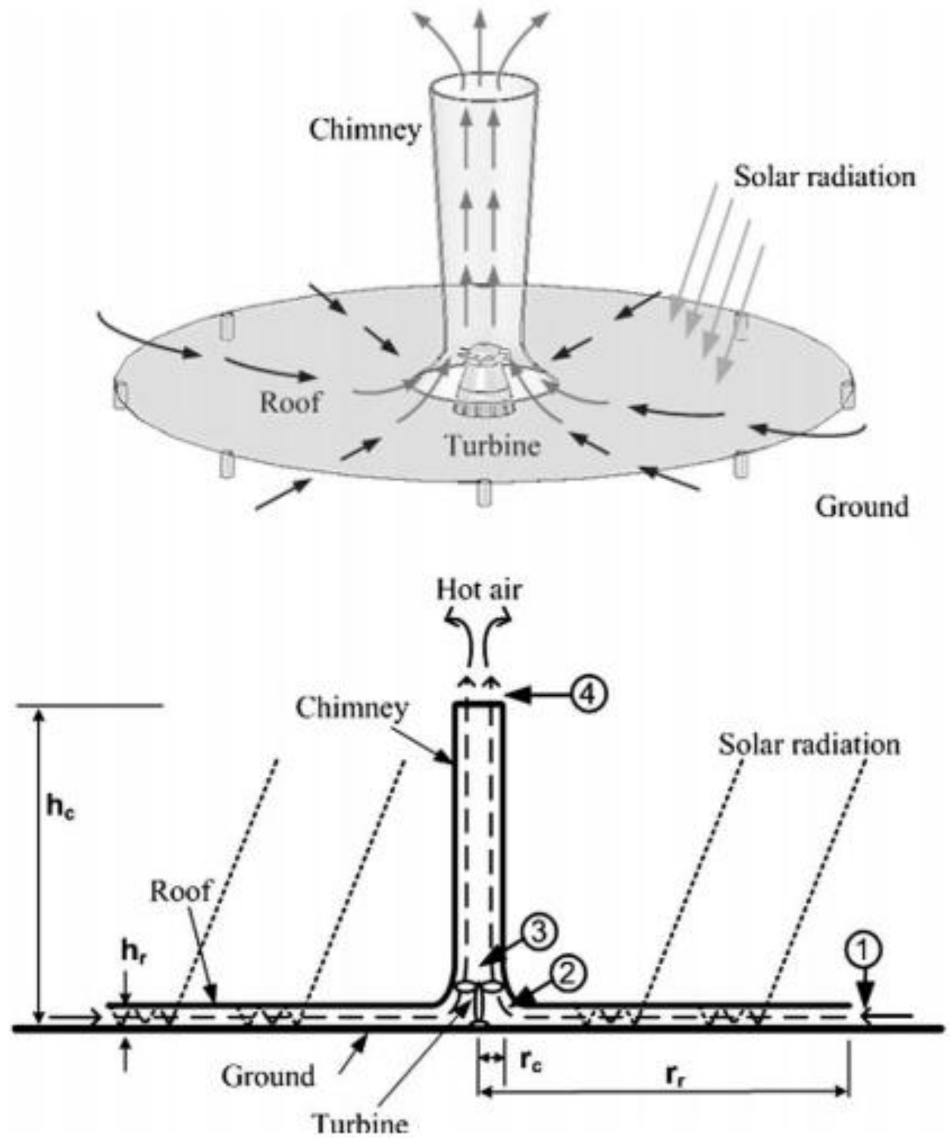
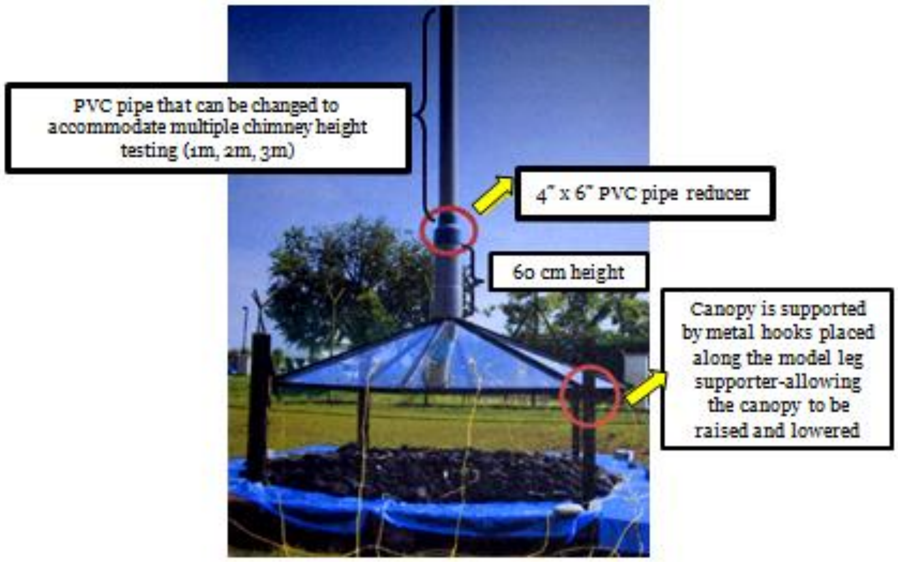
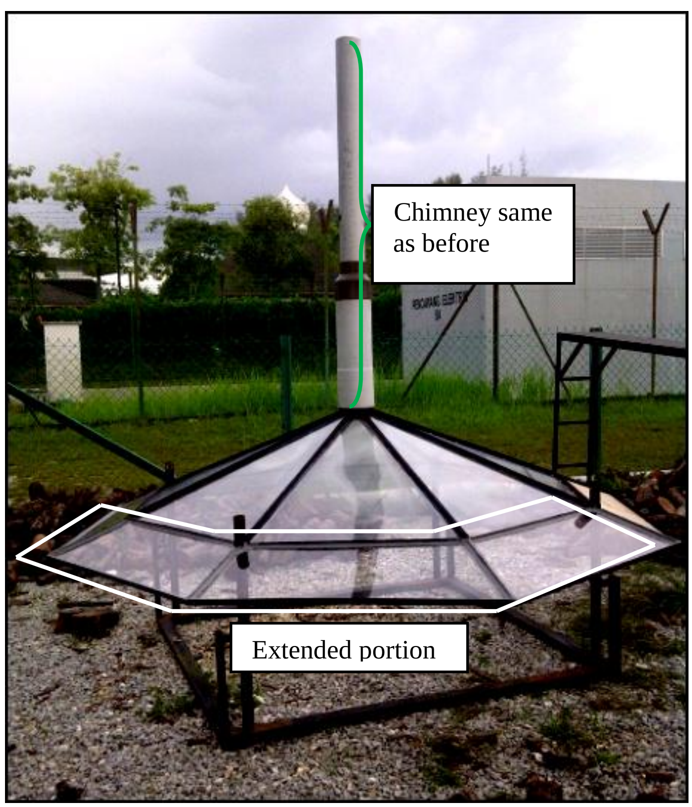
## APPENDICES

Appendix 1: Schematic Diagram of the Solar Chimney (Koonsrisuk & Chitsomboon, 2009)

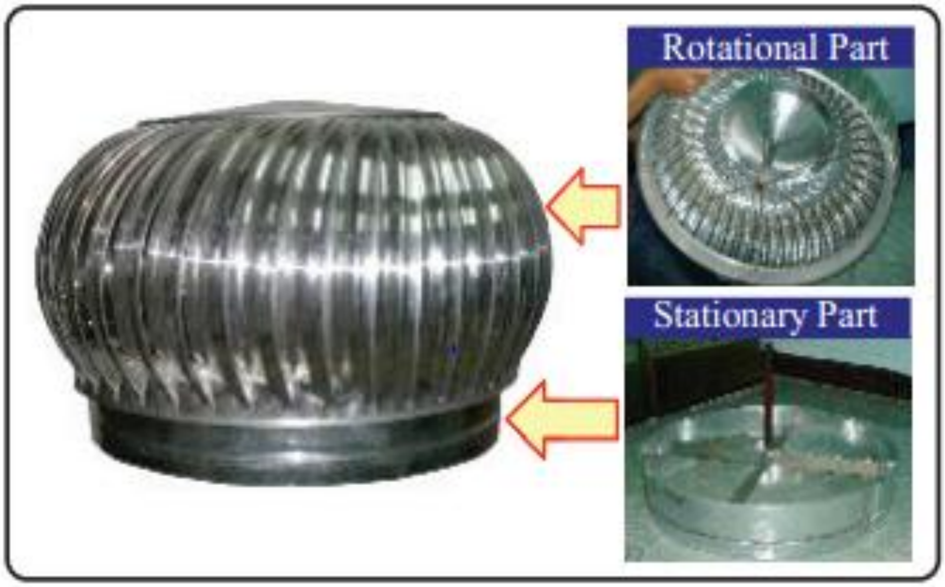


Appendix 2: Experimental Model Solar Chimney Before (Top) and After (Below) Canopy Diameter Extension



Appendix 3: Turbine Ventilator




Appendix 4: Raw data for the Cylindrical Enclosure experiment

| Time | Tf | Tc | Tg |
|---|---|---|---|
| 8:00 AM | 27.9 | 27 | 29 |
| 8:00 AM | 27.5 | 28 | 28.7 |
| 8:00 AM | 27.8 | 27.3 | 28.9 |
| 8:00 AM | 27.6 | 27.9 | 28.9 |
| | | | |
| 9:00 AM | 28 | 28.8 | 29.3 |
| 9:00 AM | 28.1 | 28.3 | 28.9 |
| 9:00 AM | 28.1 | 28 | 29.4 |
| 9:00 AM | 28 | 28.2 | 29.1 |
| | | | |
| 10:00 AM | 32 | 33.3 | 33.5 |
| 10:00 AM | 31.9 | 30 | 32.8 |
| 10:00 AM | 31.8 | 33 | 33 |
| 10:00 AM | 32.1 | 31.4 | 33.8 |
| | | | |
| 11:00 AM | 37.9 | 38.4 | 42.7 |
| 11:00 AM | 36.3 | 38.3 | 40 |

| | | | |
|---|---|---|---|
| 11:00 AM | 37.7 | 38.5 | 43.3 |
| 11:00 AM | 38.1 | 38.5 | 40.6 |
| | | | |
| 12:00 PM | 38.3 | 42.9 | 49.8 |
| 12:00 PM | 43 | 43 | 50.3 |
| 12:00 PM | 39 | 40.8 | 48.4 |
| 12:00 PM | 42.1 | 41 | 50.7 |
| | | | |
| 1:00 PM | 40.1 | 41.6 | 52.5 |
| 1:00 PM | 40.3 | 40.9 | 47.5 |
| 1:00 PM | 40.2 | 40.7 | 53.3 |
| 1:00 PM | 39.9 | 41 | 50 |
| | | | |
| 2:00 PM | 39.8 | 41.5 | 45.6 |
| 2:00 PM | 39.2 | 40.6 | 47 |
| 2:00 PM | 39 | 41.7 | 46 |
| 2:00 PM | 39.1 | 42 | 45 |
| | | | |
| 3:00 PM | 41.1 | 40.7 | 43.9 |
| 3:00 PM | 40.3 | 39.3 | 44.1 |
| 3:00 PM | 42.1 | 41.1 | 44.6 |
| 3:00 PM | 41.8 | 39.8 | 45.8 |
| | | | |
| 4:00 PM | 38.9 | 37.2 | 41.7 |
| 4:00 PM | 39 | 38.1 | 40.8 |
| 4:00 PM | 38.9 | 38.5 | 42 |
| 4:00 PM | 39.2 | 37.5 | 43 |
| | | | |
| 5:00 PM | 37.2 | 38.3 | 42.9 |
| 5:00 PM | 37.8 | 38.6 | 40 |
| 5:00 PM | 37.3 | 38.2 | 41.1 |
| 5:00 PM | 37.4 | 38.8 | 41.3 |
| | | | |
| 6:00 PM | 35.8 | 37.8 | 39.1 |
| 6:00 PM | 35.9 | 36.4 | 42.5 |
| 6:00 PM | 35.2 | 36.6 | 39.3 |
| 6:00 PM | 35.8 | 37.2 | 39 |
| | | | |
| 7:00 PM | 32.7 | 33.4 | 34.8 |
| 7:00 PM | 32.4 | 33.1 | 34.2 |
| 7:00 PM | 32.3 | 33.6 | 35.3 |
| 7:00 PM | 32.6 | 34 | 36 |

Appendix 5: Raw data for the Conical Enclosure experiment

| Time | Tf | Tc | Tg |
|---|---|---|---|
| 8:00 AM | 27.7 | 26 | 26.7 |
| 8:00 AM | 27.8 | 26.9 | 27 |
| 8:00 AM | 27.5 | 25.9 | 26.9 |
| 8:00 AM | 27.2 | 26.7 | 27.1 |
| | | | |
| 9:00 AM | 27.8 | 27.9 | 28.4 |
| 9:00 AM | 28 | 28.4 | 29.4 |
| 9:00 AM | 27.7 | 28 | 28.1 |
| 9:00 AM | 27.5 | 28.1 | 29 |
| | | | |
| 10:00 AM | 31.9 | 35 | 32.5 |
| 10:00 AM | 31.8 | 33.2 | 33.9 |
| 10:00 AM | 32.7 | 34.8 | 32.7 |
| 10:00 AM | 33 | 34.6 | 33.4 |
| | | | |
| 11:00 AM | 34.6 | 40 | 42 |
| 11:00 AM | 34.8 | 37.6 | 45.2 |
| 11:00 AM | 35 | 39.3 | 45.6 |
| 11:00 AM | 34.9 | 38.1 | 44.5 |
| | | | |
| 12:00 PM | 38.4 | 41.7 | 46.4 |
| 12:00 PM | 39.6 | 41.1 | 47 |
| 12:00 PM | 40 | 43.3 | 47 |
| 12:00 PM | 39.9 | 42.1 | 47.7 |
| | | | |
| 1:00 PM | 40.9 | 43.9 | 45.1 |
| 1:00 PM | 41 | 44.1 | 50.5 |
| 1:00 PM | 41.3 | 44.2 | 46.3 |
| 1:00 PM | 41.6 | 43.9 | 50.7 |
| | | | |
| 2:00 PM | 39.7 | 42.8 | 44.8 |
| 2:00 PM | 39.8 | 42.4 | 45.3 |
| 2:00 PM | 39.9 | 42.5 | 42.8 |
| 2:00 PM | 39.8 | 42.3 | 43.1 |
| | | | |
| 3:00 PM | 41.5 | 43 | 46.4 |
| 3:00 PM | 41.2 | 43.1 | 47.1 |
| 3:00 PM | 41.1 | 43.2 | 48.5 |
| 3:00 PM | 41.2 | 43 | 42.5 |

| | | | |
|---|---|---|---|
| 4:00 PM | 40.1 | 41.2 | 44.4 |
| 4:00 PM | 40.2 | 41.3 | 44.3 |
| 4:00 PM | 40.3 | 40.9 | 44.7 |
| 4:00 PM | 40.2 | 41 | 44.2 |
| | | | |
| 5:00 PM | 37.9 | 41.1 | 40.3 |
| 5:00 PM | 38.1 | 41.6 | 43 |
| 5:00 PM | 37.8 | 41.7 | 43.5 |
| 5:00 PM | 38 | 41.8 | 43.8 |
| | | | |
| 6:00 PM | 34.9 | 38 | 39.3 |
| 6:00 PM | 35 | 36.7 | 38.9 |
| 6:00 PM | 34.8 | 38.1 | 39.5 |
| 6:00 PM | 35.1 | 37 | 40 |
| | | | |
| 7:00 PM | 32.2 | 33.4 | 36 |
| 7:00 PM | 32.4 | 33.2 | 36.1 |
| 7:00 PM | 32.1 | 33.5 | 36.3 |
| 7:00 PM | 32.3 | 33.1 | 36.4 |