DESIGN, FABRICATION AND TEST OF VARIABLE HEIGHT SOLAR CHIMNEY

by

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Dissertation submitted in partial fulfillment of
the requirements for the
Bachelor of Engineering (Hons)
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CERTIFICATION OF APPROVAL

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A project dissertation submitted to the
Mechanical Engineering Programme
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Approved by,

(A.P. Dr. Hussain H. Jaafer Al-Kayiem)

UNIVERSITI TEKNOLOGI PETRONAS
TRONOH, PERAK
JAN 2010

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.

(TOH JIA LIN)

ABSTRACT

Solar chimney has been used for both power generation and enhancement of natural ventilation purposes. Its working principle has been discovered during the early years and has been used mainly for ventilation purposes. Solar chimney power generation concept is very much based on the air updraft, which would rotate the wind turbine located at the base of the chimney. In large power plants, the collector region could spread across the whole field in order to obtain a higher air temperature difference between the ambient and the working fluid which would then better induced the updraft. The objective of this study revolves around the parameter – variable canopy height and chimney height which would affect the performance of the collector and thereby the system.

The performance was investigated experimentally and theoretically. The theoretical model (mathematical model) is verified by comparing with Manzanares Solar Chimney. The experimental model is designed with a 2.1m canopy diameter and a 0.154 m diameter chimney inlet at the center of the canopy. The canopy is designed to provide 0.10m, 0.40m, 0.45m where else the chimney is designed for extract and retractable height of 1.6m, 2.6m and 3.6m.

This report consists of 10 chapters; introduction, literature review, methodology, theory, mathematical modeling, design and fabrication of model, measurement of model, result and discussion, recommendation and lastly conclusion. The introduction chapter offers basic understanding of the project background. Journals, paper, books and website quoted for this research are to be included in the literature review to assure the integrity of information of this project. Methodology depicts the analysis technique, milestones, tools and software needed for the research. Theory of the solar chimney explains the underlying concept of solar chimney model where else mathematical modeling reviews the equations needed for the development of the mathematical model. Design, fabrication and measurement of the model illustrate the development of the solar chimney model from scratch and ways to conduct the experiment. Experimental data collected will be tabulated, evaluated and discussed thoroughly in the remaining chapters.

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Symbols	**Units**	**Description**
C_p	J/kg.ºC	Specific heat value
D_H	m	Hydraulic diameter
f	-	Empirical factor
F	-	Collector efficiency factor
F_R	-	Collector heat transfer removal factor

g	m/s^2	Gravitational constant
h_w	W/m^2.ºC	Wind heat transfer coefficient
I_0	W/m^2	Total solar radiation
K	W/m.ºC	Thermal conductivity for working fluid
m	kg/s	Mass flow rate
q_u	W	Rate of useful heat transfer per unit collector area
T_a	ºC	Ambient temperature
T_g	ºC	Ground / collector temperature
T_c	ºC	Canopy / cover temperature
T_f	ºC	Fluid temperature
U_t	W/m^2.ºC	Collector top loss coefficient
η	-	Efficiency
ρ	kg/m^3	Air density
β	-	Air volumetric coefficient of expansion
ε_g	-	Ground emmitance
ε_c	-	Cover emmitance
τ_c	-	Canopy transmittivity
α_g	-	Ground absorbtivity
σ	W/m^2.K^4	Stefan-Boltzman constant (5.67 x 10^{-8})

CHAPTER 1

INTRODUCTION

This chapter will highlight the background study, problem statement, the main objectives of the research, scopes of study as well as the significance of the project.

1.1 GENERAL

The life span of the Sun has been estimated to be about 11billion years and the given present age of the sun is approximately 5 billion years. Therefore, renewable energy such as solar power is considered to be perpetual and inexhaustible [1]. This shows that solar energy could be used for practical purposes for ages to come even when all other energy sources such as oil and gas have depleted.

Solar chimney is a practical application of solar buildings in the enhancement of natural ventilation system by using the principle of air convection. The conventional design of solar chimney is such that it has a black painted solar chimney wall that would absorb the solar energy radiated from the sun and heat up the air inside the chimney. Given such a scenario, the temperature of the air would be higher than the ambient air temperature and thereby encourages the natural driving force of ventilation and air convection.

Solar chimney is widely used for both natural convection and power generation purposes. In this case, the aspect of solar chimney to be studied is targeted for power generation sector. Based on the research done, solar chimney is a structural design that consists of solar collector, with air inlet and outlet areas, as well as a vertical/inclined tower. Solar chimney is commonly used for power generation by incorporating a wind turbine into its design, at the base of the tower/ chimney.

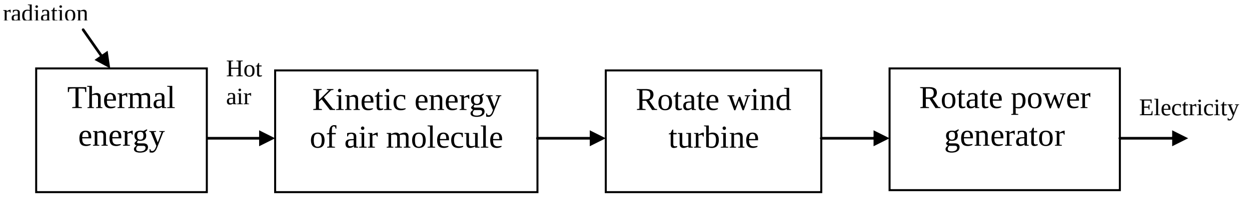


Figure 1.1: Flow scheme of energy conversion within solar chimney [2]

The solar collector will absorb a certain amount of heat from the sun radiation, thus increasing the ambient air temperature within the solar collector area. The increase of air temperature simultaneously lowers its air density. Thereby, the heated air will be guided towards the solar chimney located at the centre of the collector area and be drawn upwards and out from the solar chimney by buoyancy force. This result in lower pressure at the solar collector area, thus allowing more cold air to be drawn in and creates a natural updraft.

As the hot air is directed towards the solar chimney, the kinetic energy of the heated air molecules will turn the wind turbine located at the base of the erected solar chimney. Subsequently, the wind turbine will turn the power generator which will then generate electricity from its mechanical energy.

1.2 PROBLEM STATEMENT

Solar chimney has been widely used for ventilation purposes and been demonstrated for use as power plant. However, the performance of solar chimney in terms of variable canopy and chimney height is still unknown. Thus, the aim of this project is to verify the relationship between the variable height of the solar chimney and its effect on solar chimney collector performance.

1.3 OBJECTIVE

The objectives of this project are:

a) To design and implement experimental solar chimney with variable canopy and chimney height

b) To conduct a series of measurements to investigate the effect of canopy and chimney height on the performance of the system

c) To develop a mathematical model which is to be a simplified computer program in order to determine the solar chimney operations

1.4 SCOPE OF WORK

In this research, the aim of this study is to investigate the relationship between the variable canopy heights of solar chimney towards its performance. The scope of studies involved in this research is:-

a) The possible design of a solar chimney with extendable or retractable height

b) Ways to fabricate the prototype as per the approved design

c) Study of heat transfer mechanism within the solar chimney

1.5 SIGNIFICANCE OF STUDY

The result of this study will be evidence for the relationship between the variable canopy and chimney height to the performance of a solar chimney. Subsequent from the assembled model of a variable height solar chimney, performance measurement of the solar chimney at variable height can be gauged. The present work is an attempt to improvise the current conventional design of a solar chimney.

CHAPTER 2

LITERATURE REVIEW

This chapter will elaborate more the literature reviewed that is related to the research. The elaborations are supported by the references from the reviewed paper, journals, thesis or books.

Qureshi [1] discussed about the background, theory, design, construction and economics of solar/ wind power plant. In the paper, brief description of the 50kW plant built in Spain to demonstrate and verify the working concept is provided. The research done gave confidence in both the technical and economic viability of large megawatt scale power plant to be installed in countries within the sunny region.

Schlaich [3] analyzed the three essential components of a solar chimney power plant –solar collector, chimney and wind turbine, which enable it to convert the thermal energy from the heat collected, into kinetic energy and subsequently electrical power. The solar collector of a solar chimney refers to the glass roof canopy and the natural ground below it. The air within will be heated up by solar radiation and the water filled tubes under the roof will act as a heat storage medium. Under the stack effect, suction from the chimney draws in more hot air from the collector, resulting in more cold air being drawn in from the outer perimeter. In other words, solar radiation causes a constant updraft in the chimney. The energy is converted into mechanical energy by pressure-staged wind turbines at the base of the chimney, and into electrical energy by conventional generators. A solar chimney is highly dependent on the solar radiation. What happens when the sun is out? In this case, the water tubes lying under the glass roof act as a heat storage medium for the solar collector. It absorbs part of the radiated energy during the day and releases it into the collector at night. Thus solar chimneys produce electricity at night as well.

Bernades [4] conducted an analysis which focused on the performance characteristic of a large-scale commercial solar chimney. The analysis technique begins with the development of a mathematical model which was then validated with the experimental data of Manzanares. The mathematical model initiated by having assumptions that the temperature of the 'boundaries' surrounding the air streams are uniform and the temperatures of the air streams vary linearly along the collector. A long collector is assumed to be divided equally into finite number of short collectors. The iterative process will be repeated until all consecutive mean temperatures only differ by less than a desired value. By the analysis method mentioned above, the required temperature along the entire length of the collector, height of the chimney, mass flow rate and generated power in the turbine can be obtained. The iterative program flowchart (Figure 2.3) of [4] is used as a reference to the analytical mathematical model solver for this research.

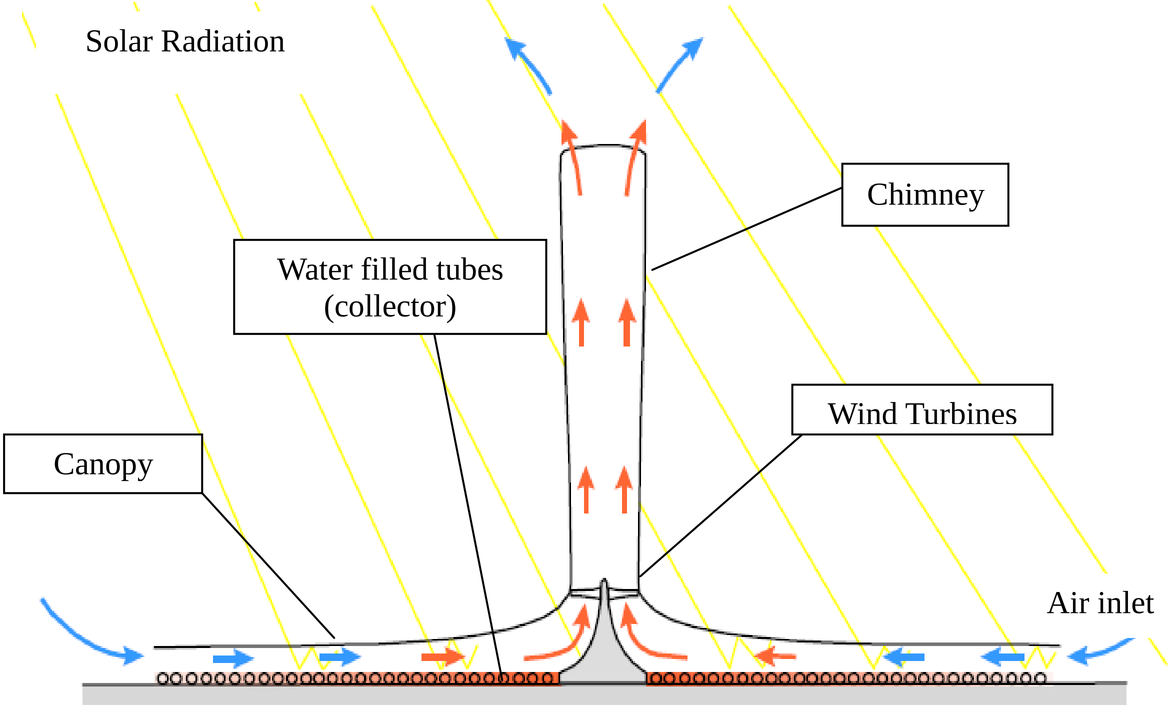


Figure 2.1: Schematic drawing of the air flow inside the solar chimney [3]

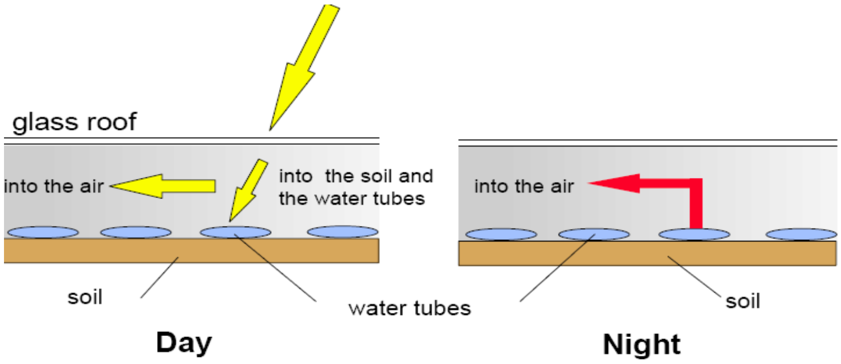


Figure 2.2: Principle of heat storage under the roof by using water filled tubes [3]

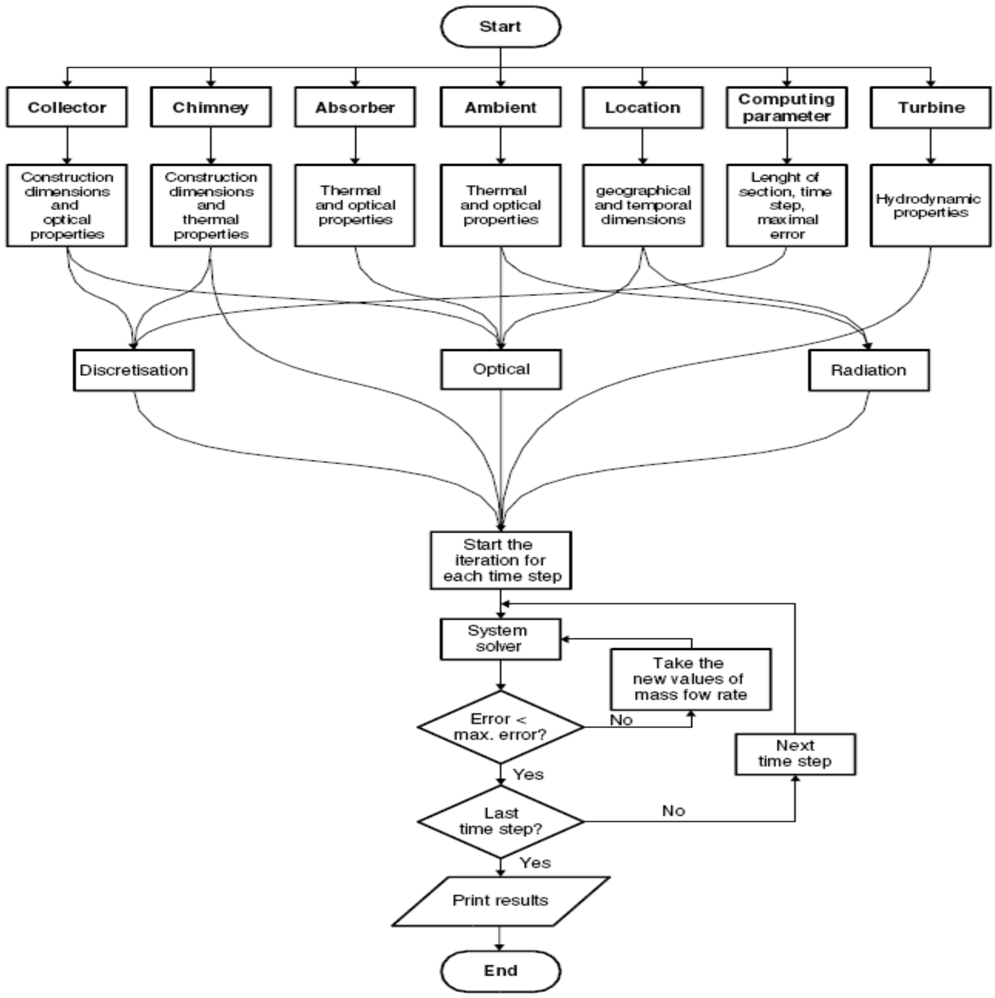


Figure 2.3: Flowchart for computer iterative solution program of Bernades [4]

In addition to that, [4] showed that the factor of pressure drop at the turbine and the transmittance of the collector are of great importance as well. Supplementary parameters such as ground heat penetration coefficient and distance between absorber and ground demonstrated no significant effect on the energy output but conversely for power output vs. time.

Ninic [5] involved the study of the dependence of the work potential of the air flowing into the collector utilizing the heat inside the collector, air humidity and atmospheric pressure as a function of elevation. The collector types analyzed in this study are using dry and humid air. As a result, the influences of various chimney heights on the air work potential are established. Part of the research studied the role of a solid chimney by considering the chimney is used to separate the elevating air (heated air) from the surrounding atmosphere. Thus, meaning the chimney will eliminate pressure differences all along its length. Based on the model developed, the ratio between the theoretical works available from a specific chimney height to the heat assumed in the collector can be taken as definition of the chimney's efficiency or as buoyancy conversion efficiency where it is a product of both theoretical and relative chimney efficiency. The relative chimney efficiency takes into account the limited height of the chimney.

Shyia [6] aimed to compare the available techniques of solar water pumping and select the best suitable one for Iraq conditions. The effect of variable canopy height and absorbing material on the performance of solar chimney was studied as well. Experimental and numerical analysis was adopted for the research targeted for the calculation of ground temperature (T_g), collector's temperature (T_{cover}) and the pressure drop along the chimney.

The result of the research showed that ground collector absorbing material increases collector air temperature rise and the best performance of the solar chimney is when the canopy film height is 0.1m above ground. The researcher concluded that under the Iraq radiation condition, large scale solar chimneys are recommended for power plant services.

Al-Nakeeb [7] did a computational analysis of the geometry alteration on the performance of a solar system to generate air flow. This investigation was carried out by using numerical analysis based on the Finite Difference Technique. His result showed that the change of cover orientation in the solar collector have considerable effects on the performance of the system. The detail mathematical modeling simulation of [7] was used as a reference to this study's model simulation.

Besides that, [7] researched on the effects of different collector cover orientation (0°, -0.5°, -1°, 0.5°). Computational analysis showed that the velocity at the inner radius of the collector (connection between the chimney and the collector cover) when it is orientated at 0.5° is twice of that at 0°. The increase in velocity is combined with reduction in the working mass flow rate and efficiency. The highest efficiency is obtained when the cover is set at -1°, the velocity is low but the working mass flow rate is very high and the efficiency is improved by about 38% when compared with the reference state (0°).

Sekhar [8] researched on the heat loss coefficients in solar flat plate collectors. Study showed that the as the emissivity of the absorber plate increases, the top loss coefficient increases as well, which in turn imposed significant effects on the collector's efficiency. In addition to that, the efficiency is found to increase with increase in ambient temperature due to reduction in heat loss from the system.

Chua [9] researched the development of hybrid solar chimney which utilized both the flue gas and solar as heat generators. Based on his research, the solar intensity of Tronoh, Malaysia is found to range from 90 W/m^2 to 610 W/m^2. The data was taken from morning (9am) until mid afternoon (4pm). This data is to be taken as the primary estimation of the solar intensity for the analytical simulation tool.

CHAPTER 3
METHODOLOGY

This chapter depicts the analysis techniques used, the project flow chart, the mathematical model simulation flow chart, FYP 1 and FYP II Gantt Charts as well as the tools and software required for smooth execution of this research.

3.1 ANALYSIS TECHNIQUE

The methodology used to design and fabricate an experimental model of variable height solar chimney are:-

1. Analytical
2. Model design and fabrication
3. Experimental

3.2 PROJECT FLOW CHART

The overall project execution flow chart (Figure 3.1) depicts the procedures and steps taken through the project conducted, analyzed and troubleshoots throughout the research period. While the mathematical model program flow chart (Figure 3.2) refers only to the simulation solution steps taken in order to reach a plausible estimation of the ground and canopy temperature of the model.

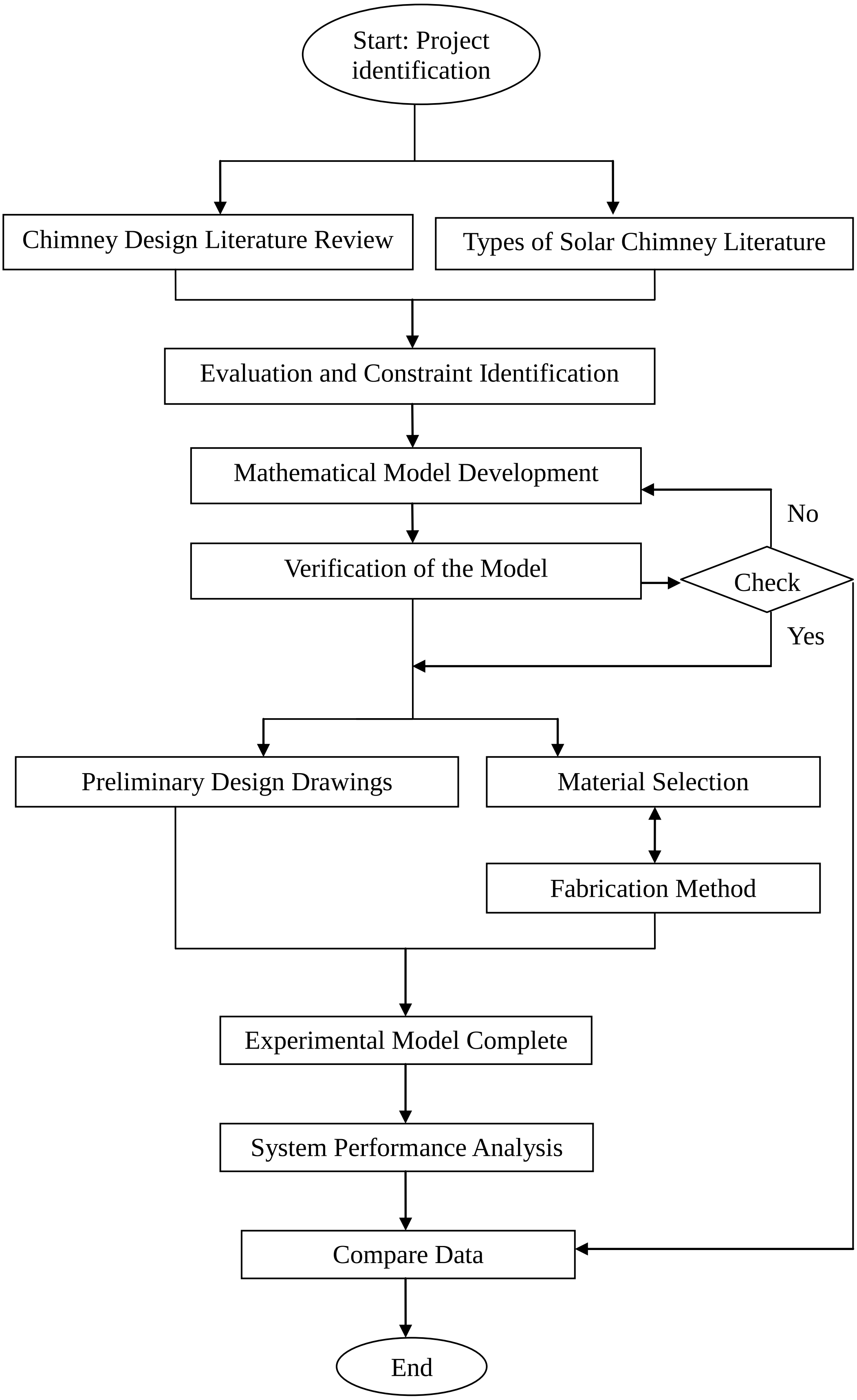


Figure 3.1: Project execution flow chart

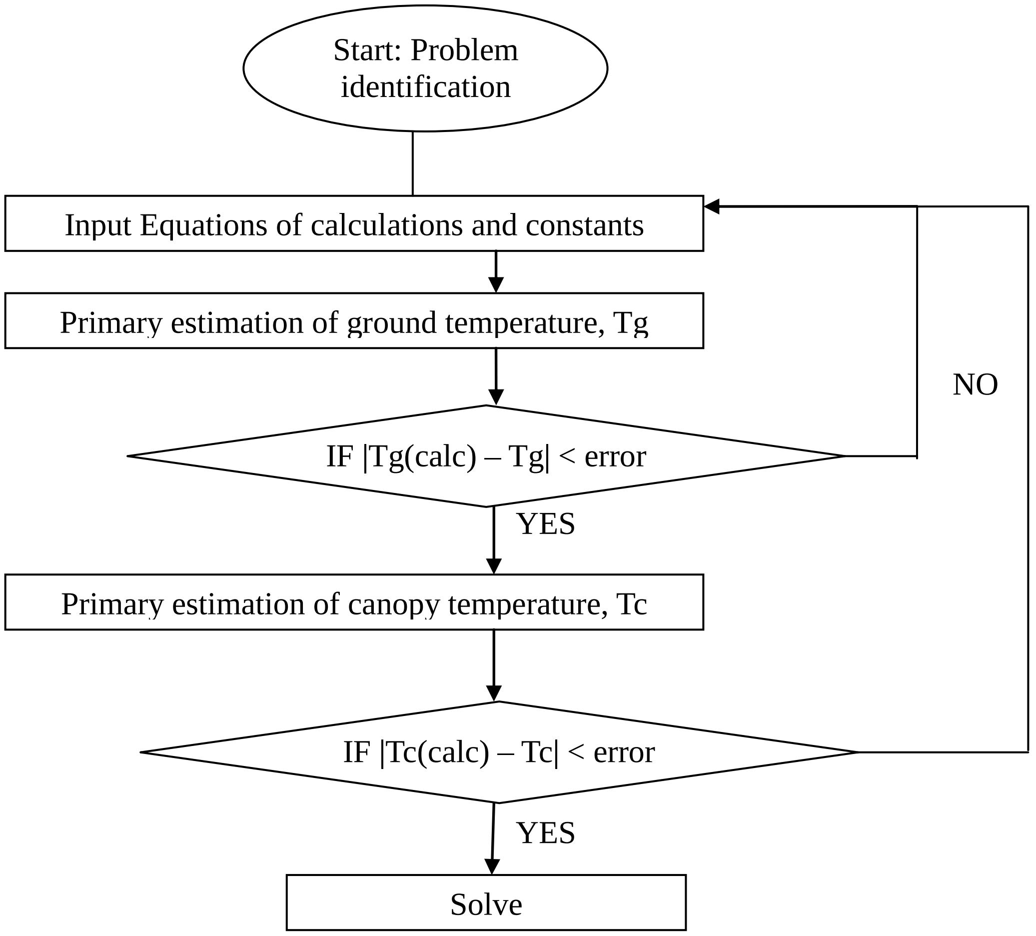


Figure 3.2: Mathematical model program flow chart

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 GANTT CHART AND MILESTONES FOR FYP 1

Table 3.1: Gantt chart and key milestones for FYP I

No	Detail Week	1	2	3	4	5	6	7	8	9		10	11	12	13	14
1	Data Gathering and researches	■	■	■	■	■	■	■	■	■	Mid Semester Break	■	■	■	■	■
2	Preliminary report				■											
3	Mathematical model development				■	■	■	■	■							
4	Preliminary design of chimney					■	■	■	■	■						
5	Progress report								■							
6	Seminar								■							
7	Material selection					■	■	■	■	■		■	■			
8	Fabrication method					■	■	■	■	■		■	■			
9	Finalised design of chimney													■		
10	Interim Report Final Draft															■
11	Oral Presentation											During Study Week				

3.4 GANTT CHART AND MILESTONES FOR FYP II

Table 3.2: Gantt chart and key milestones for FYP II

No	Detail Week	1	2	3	4	5	6	7		8	9	10	11	12	13	14
1	Data Gathering and researches	■	■	■	■	■	■	■		■						
2	Validation of Mathematical Model	Completed during Semester Break														
3	Installation of Model	■	■						Mid Semester Break							
4	Experimentation	■	■	■	■	■	■	■								
5	Progress Report I				■											
6	Compare Analytical and Experimental Data									■	■	■				
7	Progress Report II									■						
8	Seminar									■						
9	Poster Exhibition												■			
10	Dissertations Final Draft															■
11	Oral Presentation									During study week						
12	Dissertations (hard bound)									7 days after oral presentation						

3.5 TOOLS REQUIRED

a) Solarimeter

b) Portable hot wire anemometer

c) Thermocouple wires

d) Solar Chimney Model with variable height

e) Data Logger

3.6 SOFTWARE TO BE USED

a) AUTO CAD

b) Microsoft office Excel

c) Microsoft office Word

CHAPTER 4

THEORY OF SOLAR CHIMNEY

As defined in Chapter one, solar chimney power plant comprises of three technologies, namely solar air collector, the wind turbine and the chimney. Figure 4.1 sketch shows the different parameters of the power plant.

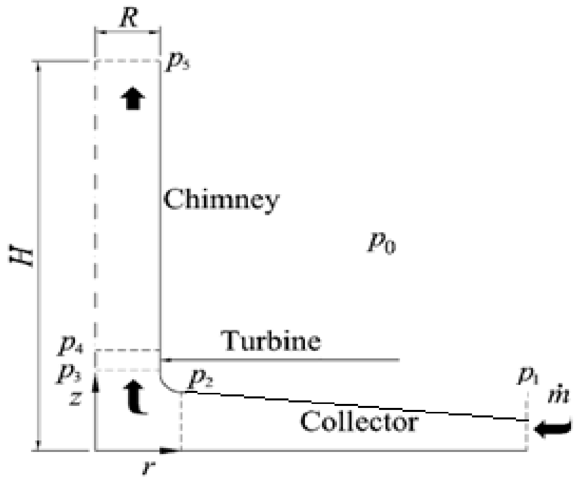


Figure 4.1: Sketch of the air flow in a solar chimney [4]

Referring to the figure above;

$\dot{m}$ = air inlet mass flow rate

r = radius of the solar chimney

p_0 = surrounding air pressure

p_1 = inlet air pressure

H = height of chimney

p_2 = collector outlet pressure

p_3 = turbine inlet air pressure

p_4 = turbine outlet air pressure

p_5 = chimney outlet air pressure

R = radius of chimney

Collector related: Type of Solar Air Collector Used

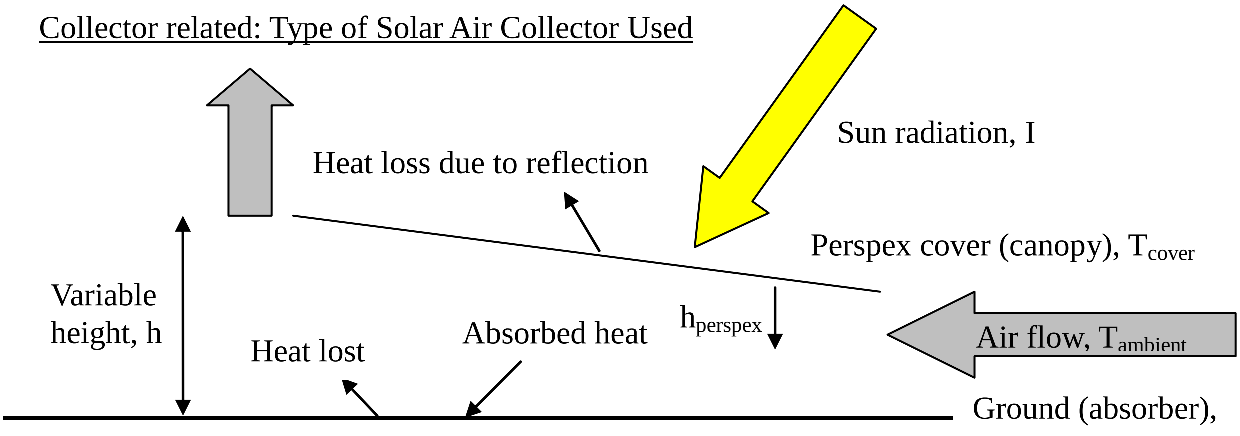
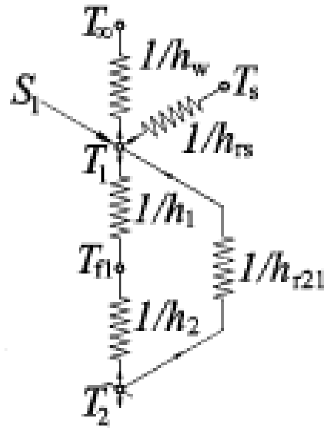


Figure 4.2: Sketch of solar collector thermal network

- Single layer Perspex cover
- Absorber/ Collector: ground (sand)

The thermal network of a solar chimney can be analyzed as shown in Figure 4.3, where,



h_{r21}= $h_{r,g\text{-}c}$
= Radiation heat transfer coefficient (ground – canopy)
S_1 = Total sun radiation = I_0
h_w = Convection heat loss by wind from canopy
h_{rs} = Sky radiation heat transfer coefficient from canopy
T_∞ = Ambient Temperature = T_a
T_s = Sky Temperature = $0.0552T_a^{1.5}$
h_1, h_2 = Convection heat transfer coefficient for cover and ground respectively to air

Figure 4.3: Thermal network of Solar Collector

Solar radiation from the sun penetrates the transparent canopy to heat the ground which in turns heat up the adjacent air. Some of this radiation is absorbed by the canopy. Similarly, the heated ground radiates heat to the canopy and also there is a convection heat transfer between the air and the canopy.

Heat losses from the canopy are due to wind convective heat transfer to the ambient air and radiation heat loss to the sky from the canopy/cover. Mathematically the energy equations can be stated as follows:

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:

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

Referring to Figure 4.2, the following assumptions are made:

a) Air inlet temperature, T_{in} = Ambient temperature, $T_{ambient}$
b) Steady flow of air is available

c) The thickness of the Perspex cover is uniform throughout
d) Inclination angle of cover has no significant impact on the top loss coefficient
e) The variation of temperature is so small that change in viscosity and thermal conductivity is negligible.
f) Air density is constant throughout the collector until turbine's outlet
g) No ground overall heat loss, U_b due to insulation.

Governing equations of the system [10]:

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

$$q_{convection} = hA\,(T_s - T_\infty)$$

Where h = convection heat transfer coefficient and

$$q_{rad} = \epsilon\sigma A\,({T_s}^4 - {T_{sur}}^4)$$

Given,

T_s = surface temperature which in this case refers to glass cover temperature, T_{cover}

T_{sur} = surrounding temperature which in this case refers to ambient temperature, T_{amb}

T_∞ = Fluid temperature which in this case refers to air temperature, T_f

A = surface area

ϵ = emissivity

σ = Stefan – Boltzmann constant = 5.67×10^{-8} $W/m^2 . K^4$

To find the mass flow rate

Referring to Figure 4.1, $\dot{m}$ signifies the air mass flow rate in the system. It can be calculated by using the equation where the system is at steady state;

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

Where ρ_{air} = density of air in the system

A_c = cross sectional area at any point from inlet to exit of the chimney

V = Speed of air flow at any point in the system= V_f

Cross sectional area of chimney is used under these circumstances because it is assumed that the mass flow rate is constant throughout the system.

Chimney related

Having the air heated up and rising upwards and out from the solar chimney outlet, it creates an up draft of air thus enhancing natural convection flow. Due to the varying density of air and the varying height of the canopy, there exists a difference in pressure.

Given that change in pressure, $\Delta p = \rho.g.H$

Where ρ = density of air

g = gravitational constant

H = Variable chimney height

To find the pressure difference produced between the tower based (collector outlet) and the ambient:

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

The pressure difference can be sub-divided into static and dynamic component, provided friction losses are neglected:

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

The static pressure difference describes the drop of pressure at the turbine; where else the dynamic component describes the kinetic energy of the flow. Assuming that $\Delta p_{static} = 0$, the power contained in the flow now is:

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

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

$$\eta_{tower} = \frac{P_{total}}{\dot{Q}}$$

Where $\dot{Q}$ = heat flux

The electric power generated by the turbine generators, P_{out} can be expressed as

$$P_{out} = \eta_{tg}.\Delta p_t\ .V_f.A_c$$

Where η_{tg} = efficiency of turbine generators

Δp_t = pressure losses across the turbine

V_f = flow velocity

CHAPTER 5

MATHEMATICAL MODELLING

The objective of the Mathematical Model was to solve for the system's performance through iteration method. As the solar radiation hit the collector's surface (canopy), made out of a single layer of Perspex; heat is radiated as well as absorbed and later transmitted to the ground which in turns heat the air by convection under the canopy. The ground which acts as the storage medium collector in this system will absorbs heat from the sun transmitted via the canopy and gradually losses its heat content to the air.

5.1 ASSUMPTIONS

a) Constant air flow.
b) The system is steady.
c) Air viscosity (μ) and air thermal conductivity (K) are constant.
d) Value of density stay constant from the end of the collector till the outlet of wind turbine.
e) The gas behaves as ideal gas

5.2 COLLECTOR PERFORMANCE EQUATIONS

The solar heat energy gain can be evaluated from energy balance equation to predict performance and efficiency of the solar collector, correct the values of temperature for the cover (canopy) and the ground by suitable iterative processes as shown in the equations below: [11]

<u>To find solar heat energy gain</u>

$$q_u = F [S - U_L (T_f - T_a)]$$

Where

S $= I_0 (\alpha_g \tau_c)_e$

I_0 = Solar radiation

T_a = Ambient temperature

T_f = Fluid temperature

$(\alpha_g \tau_c)_e$ = Effective transmittance-absorbency product = 1.01 $\alpha_g \tau_c$ [6]

$$F = (1 + \frac{h_{r,g-c} . U_t}{h_{r,g-c}h_1 + h_2U_t + h_2h_{r,g-c} + h_1h_2})^{-1}$$

Where

F = Collector efficiency factor

$$U_L = \frac{U_t}{1 + (U_t h_2)/\ (h_1 h_2 + h_1 h_{r,g-c} + h_2 h_{r,g-c})}$$

Where

U_L = Overall heat transfer coefficient

$h_{r,g-c}$ = Radiation heat transfer coefficient from the ground to the cover

$$= \frac{\sigma(T_g{}^2 + T_c{}^2)(T_g + T_c)}{\left(\frac{1}{\varepsilon_g}\right) + \left(\frac{1}{\varepsilon_c}\right) - 1}$$

U_t = Top loss coefficient defined by the following empirical equation [11]

$$U_t = \left[\frac{N}{\left(\frac{344}{T_g}\right)[\frac{(T_g - T_a)}{(N+f)}]^{0.305}} + \frac{1}{h_w}\right]^{-1} + \frac{\sigma\left(T_g + T_a\right)(T_g{}^2 + T_a{}^2)}{[\varepsilon_g + 0.0425N\left(1 - \varepsilon_g\right)]^{-1} + \left[\frac{2N + f - 1}{\varepsilon_c}\right] - N}$$

Where

N = Number of covers

ε_g = Emissivity of ground

ε_c = Emissivity of canopy

f = $(1 - 0.04h_w + 5.0 \times 10^{-4}\ h_w^2)\ (1 + 0.058N)$

h_w = Wind heat transfer coefficient

= $5.7 + 3.8\ V_w$

Where V_w = wind velocity

h_1, h_2 = Heat transfer coefficient for cover and ground respectively

Using

Nu = $0.0158\ Re^{0.8}$ and h_1 or $h_2 = \frac{Nu.K}{Dh}$

Where D_H = hydraulic diameter of collector's flow field

$$= \frac{4(flow\ area)}{wetted\ perimeter}$$

$$= \frac{4(2\pi r\delta)}{2.2\pi r}$$

= 2H

Where Nu = Nusselt number

Reynolds number is essential to determine the heat transfer rate for cover and ground. According to Crowe, Reynolds number is a dimensionless number that depicts the ratio of inertial forces to viscous forces [13].

Where, Re = Reynolds number

$$Re = \frac{\rho V D_H}{\mu} = \frac{V D_H}{\nu}$$

ρ = density of air (kg/m3)
V = mean velocity (m/s)
D_H = hydraulic diameter (m)
ν = kinematic viscosity
μ = dynamic viscosity

$$T_g = T_a + \left(\frac{q_u}{U_L.F_R}\right)(1 - F_R) \qquad \text{...........................(5.1)}$$

Where F_R = Collector heat transfer removal factor

$$= \frac{\dot{m}C_p}{A_c.U_L}\left[\,1 - e^{-\left(\frac{A_C U_L F}{\dot{m}C_p}\right)}\right]$$

$$T_c = T_g - \frac{U_t(T_g - T_a)}{h_{g-c} - h_{r,g-c}} \qquad \text{.............................(5.2)}$$

Where

h_{g-c} = convection coefficient between ground and the canopy

$$= \frac{Nu.K}{\delta}$$

Where δ = height of cover from the ground

Nu = Nusselt number for this case is evaluated by [12]

While Nu = $0.152\ (Gr)^{0.281}$

Gr = Grashof number

$$= \frac{g\beta \Delta T_{g-c} \delta^3}{v^2}$$

Where g = gravitational constant

ß = volumetric coefficient of expansion of air (1/T for ideal gas)

ΔT_{g-c} = temperature difference between the ground and canopy

v = kinematic viscosity of air

Note: Equation 5.1 and 5.2 are to be solved iteratively.

<u>To find collector efficiency</u>

$$\eta_c = \frac{C_p \dot{m} \Delta T}{\pi {R_c}^2 I_0}$$

Where

$\dot{m}$ = air mass flow rate

ΔT = collector air temperature rise ($T_f - T_a$)

R_C = radius of collector

I_0 = solar radiation

The mathematical model is simulated using Microsoft Office Excel and solve using its Goal Seek function. By inputting the geometry and weather data, primary estimation of the ground and canopy temperature, T_g and T_c, the model will solved for the other data. Subsequently, using the equation 5.1 and equation 5.2, both T_g and T_c, will be solved.

CHAPTER 6

DESIGN AND FABRICATION OF SOLAR CHIMNEY MODEL

Considering the fact that the purpose of this projects revolves around the design and fabrication aspect of the variable height solar chimney, evaluation and design constraint identification on the model was done.

Before the design procedure is discussed, the design constraints identified is as listed below:

6.1 DESIGN CONSTRAINTS

a) Weight issues

- The weight of the model should not be higher than the sustaining holding weight of the base (plywood plate)
- Light weight materials should be considered as parts of the construction material. For example: PVC tubes for the construction of solar chimney
- The canopy cover material lies between glass and Perspex. For lighter weight, Perspex will be an optimal selection.

b) Stability of model

- The canopy is to be raised from its datum height and the chimney height is to be lengthen for more detailed case study. Given the maximum height of the chimney (approximately 4m), and the drastic change in wind condition of Malaysia, there is a possibility that the prototype may collapse.
- Steel frame work is to be input between Perspex joints for the canopy to strengthen the structure. In addition to that, steel frame leg supporters are to be placed at the peripherals of the canopy (90 degrees apart) for extra weight and stability support.

6.2 DESIGN CRITERIA

For the preliminary design state of solar chimney model,

1. Local weather data is surveyed. For example, solar intensity, ambient

temperature and wind velocity.

2. Model installation location is decided depending on availability of space, due to the massive size of the structure.
3. The dimensions of the model are decided based on standard measurements of solar chimney prototype.
4. Data acquisition on the optical properties of the collector (ground) and the canopy (Perspex).
5. The overall performance of the collector is to be simulated and investigated through the mathematical model developed using the mathematical relations as mentioned in previous chapter.

6.3 MATERIAL SELECTION

Table 6.1: Pugh Selection Matrix for canopy's material

Materials Design criterion	Criterion Weightage	Perspex	Glass	Tedlar (PVF)
Transmittance	0.33	4	5	4
Availability	0.20	5	4	3
Strength against breakage	0.25	4	2	4
Cost	0.22	4	3	3
Total	1.00	4.20	3.81	3.58

Scale:-

4-5	above acceptance range
3	within acceptance range
1-2	below acceptance range

Referring to the Pugh Selection Matrix above, it showed that Perspex is the optimal material choice for the canopy. Reason being, it is easily available, low cost, high transmittance and more durable as compared to other materials. Glass may have the same advantages as Perspex in terms of availability and transmittance factor, but its brittle nature and its high susceptibility to breakage under impact are indeed matters to be taken into consideration. Tedlar, also known as poly vinyl fluoride sheet, used in the Manzanares Solar Chimney power plant, would be an optimal choice for huge plant development for it is cheaper in bulk. Thus, its high cost had it ruled out.

The material for the solar chimney is normal grade PVC pipes. Due to its availability and light weight, low cost and its ease of installing, it had become the prior choice for the structure as compared to others materials such as concrete and steel bar.

6.4 PRELIMINARY MODEL DESIGN

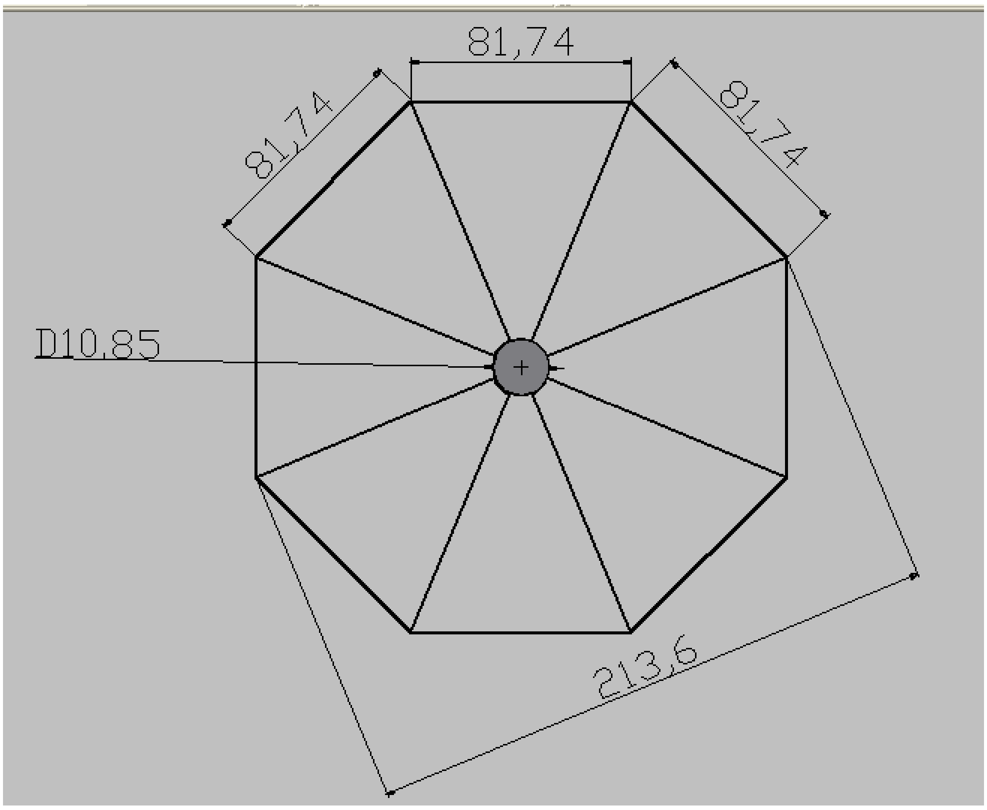


Figure 6.1: Plan View of Solar Chimney (After Extrusion of Chimney) in cm

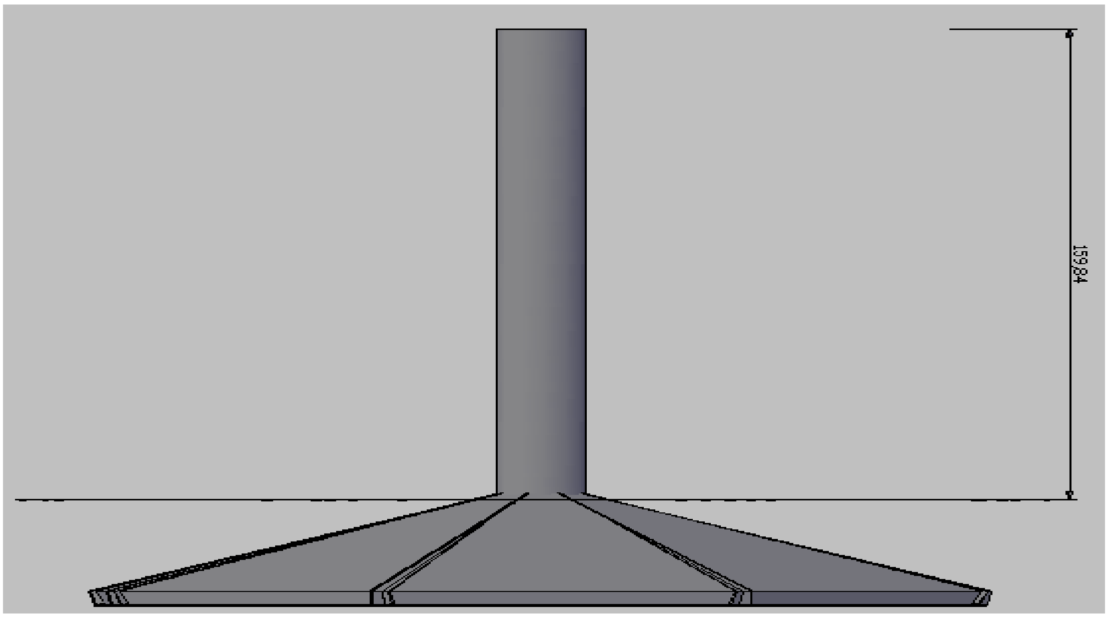
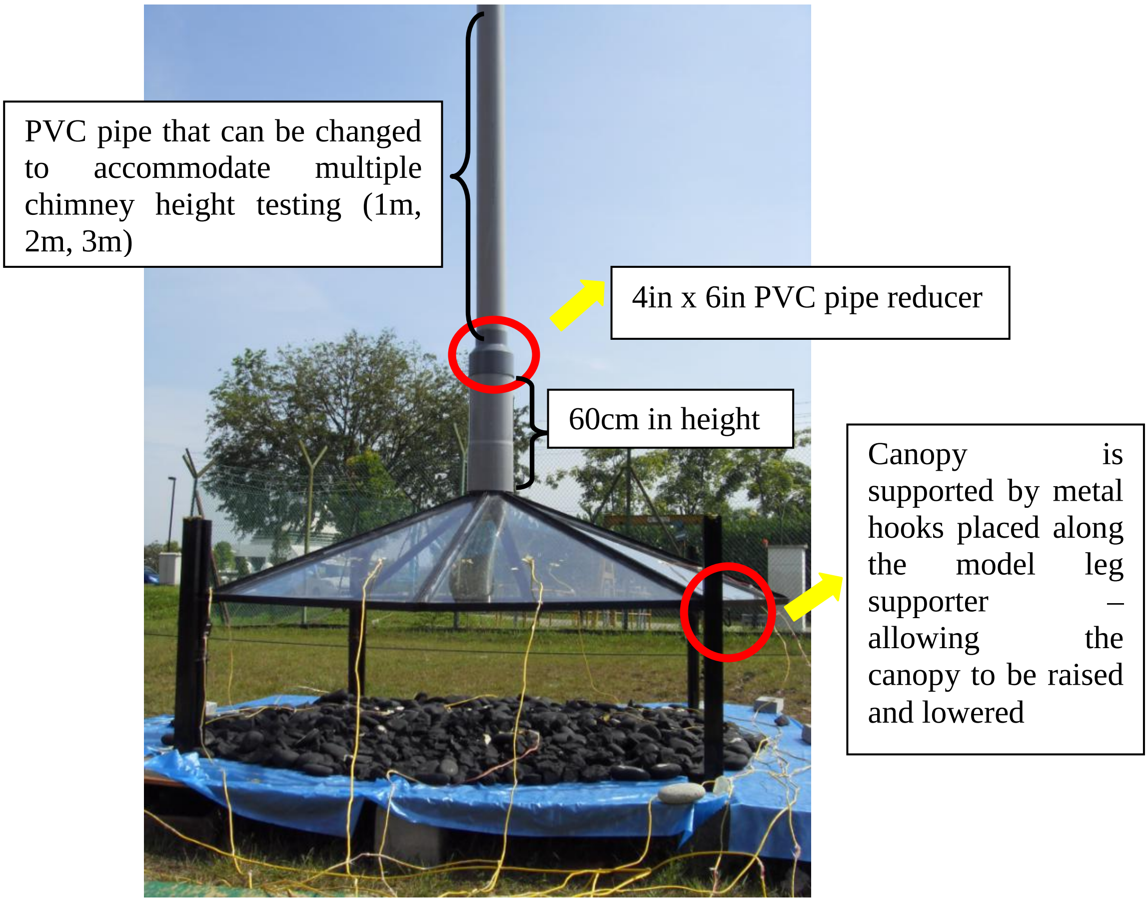


Figure 6.2: Side View of Solar Chimney in cm

6.5 FINAL MODEL DESIGN



PVC pipe that can be changed to accommodate multiple chimney height testing (1m, 2m, 3m)

4in x 6in PVC pipe reducer

60cm in height

Canopy is supported by metal hooks placed along the model leg supporter – allowing the canopy to be raised and lowered

Figure 6.3: Picture of solar chimney model used for experimental work

The final model is made up of three parts; the collector, canopy and the chimney. Figure 6.3 shows the experimental model.

Collector

The collector for the experimental model is made up of rocks that are fully painted with black non-shiny paint in order to increase its absorbtivity. The black painted rocks are lay all across the area below covered by the canopy to ensure better data.

Figure 6.4: Black painted rocks as the heat collector medium of the model

Canopy

The canopy is constructed of eight Perspex triangles each of 81.7x 107x107cm, all together making an octagon of 2.1m in diameter and of a thickness of 4mm. The eight Perspex triangles are laid on top of multiple L-shaped steel frames that are welded together at its joints.

The canopy is designed with 20º slope angle providing height difference at the inner radius of canopy, R_{c1} and outer radius of canopy, R_{c2}. The slope angle is necessary to provide a better air flow streamlining and to avoid the abruptness of air convergence (from the ambient to the model air inlet) which will increase the flow resistance. Besides that, the slope also avoids any dirt or water accumulation on the surface of the Perspex pieces. With every downpour, the rain will wash the dirt on the Perspex away, leaving it clean and its transmission undisturbed.

The canopy is designed in such a way that it can be raised with just a light pull upwards without the assistance of car jacks or any other mechanical equipment. The canopy is then supported using a metal hook that is to be placed into the pre-drilled hole at the metal frame of the model. The design provides three different height of the canopy from the ground level. At the inlet, the height may be adjusted to 30cm, 40cm, 45cm, 50cm and 55cm. However, only the first three heights mentioned (30, 40, 45) are to be tested.

Figure 6.5: Canopy leg support with pre-drilled holes

Figure 6.6: Metal hook for canopy adjusts

Due to the need to *vary the height of the solar chimney*, accessibility to the centre of the model (the chimney) is necessary. However, given that the distance from the centre of the model to the edge of the canopy is approximately 1.07m, making it difficult to access the chimney; some modification to the model was necessary.

Solution provided was to have two out of the eight pieces of Perspex are to be screwed to the steel frames so that the Perspex pieces can be extracted and allowed one to access the solar chimney . Where else the other six Perspex pieces can be glued to the steel frame using silicone super glue which minimizes the heat loss and able to effectively hold the Perspex pieces to the steel frame.

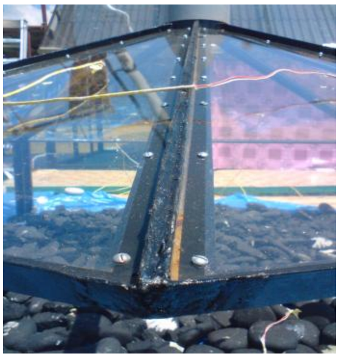


Figure 6.7: Canopy joints with extractable Perspex pieces

Chimney

The solar chimney used is a standard grade PVC pipe of 0.1m diameter. The solar chimney is separated into two parts where the bottom of the chimney is design for the installation of a turbine for future testing. The turbine to be used by the subsequent researcher is of a diameter 0.15m. Therefore, modification to preliminary design of the solar chimney is necessary.

Solution being to have a standard PVC pipe of 0.15m (6in) diameter connected to the 0.1m (4in) diameter pipe using a PVC reducer joint. The 6in PVC pipe is designed in such a way that there is an opening which allows one to have access to the turbine within.

The 6in diameter pipe will then sits on a metal chimney flanges which is to be welded to the canopy metal frame, providing absolute stability to the chimney above.

Figure 6.8: 6in pipe with an opening for turbine accessibility

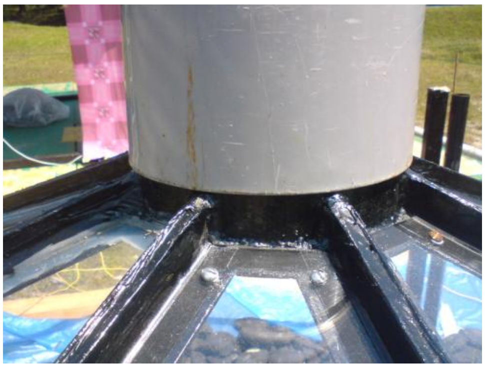


Figure 6.9: Solar chimney pipe sitting on the chimney metal flange welded to the canopy's frame

The 4in pipe is to be connected to the 6in pipe using a 4in x 6in PVC reducer. Given that the research requires studies to be done on different heights of solar chimney (1m, 2m, 3m), the 4in pipe is not glued to the reducer. Thus, it would be easy for one to detach the 4in pipe of 1m height and changed it with a 2m 4in diameter pipe.

The same goes for the 3m 4in diameter pipe.

CHAPTER 7

EXPERIMENTAL DATA MEASUREMENTS

The main variables to be measured in this research are the ground and canopy temperature, airflow, and solar intensity of the model. The measurement equipments used are as shown in the figure below.

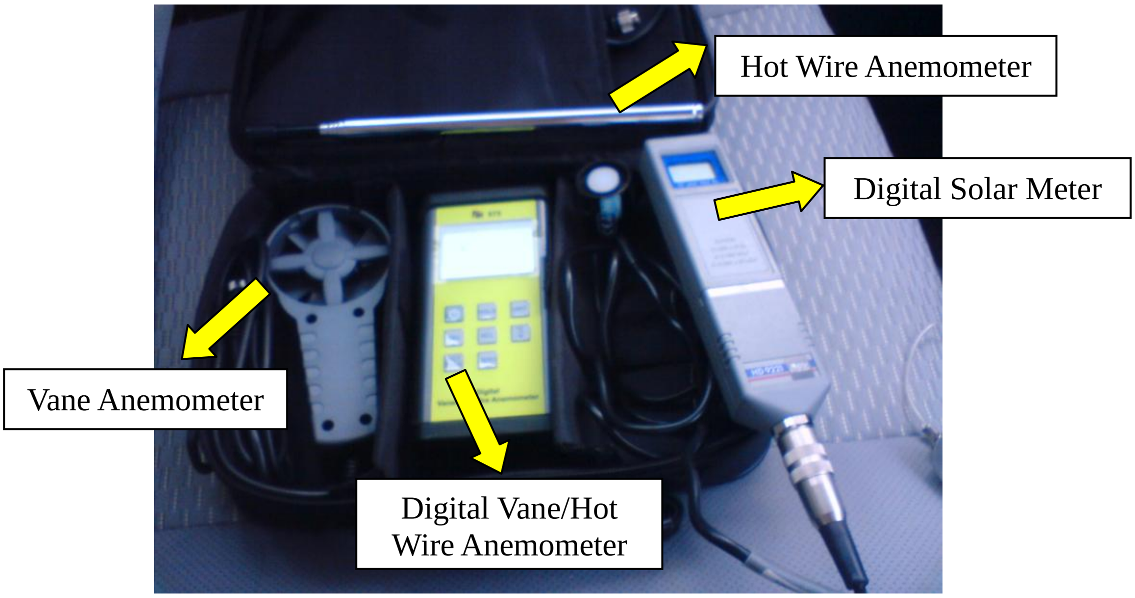


Figure 6.10: Measurement equipment

Figure 6.11: Temperature data logger

7.1 TEMPERATURE MESUREMENTS

For better results, it is required to measure the ground and canopy temperature at more than one location. For the canopy temperature, each surface temperature of the Perspex pieces is taken into considerations. Given that the model is located at an open area where the sun radiation is not obstructed by any tall building, and the sun rays hits the Perspex surface fully, it is assumed that the surface temperature of a piece of Perspex is equal throughout its exposed area. However, for a more average reading, the thermocouple wires are to be placed at the centre of each Perspex pieces.

The thermocouple wires are then attached to the data logger, allowing easy reading of the temperature data of both canopy and ground temperature. Given that there are eight pieces of Perspex and the collector area is of a circle, eight thermocouple wires are attached to each Perspex pieces and four more for the collector temperature data.

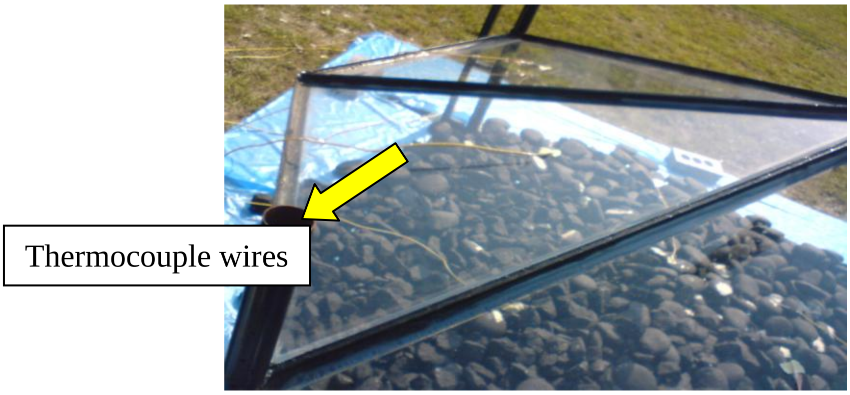


Figure 6.12: Thermocouple wires on Perspex surface for data logging

Figure 6.13: Thermocouple wires on collector (black painted rocks) for data logging

Given that the sun rises from the left and sets from the right of the model, the ground temperature data should be acquired from all four directions for better data captured.

7.2 VELOCITY MEASUREMENT

The main device used for the air flow velocity measurement is a digital vane anemometer and the hot wire anemometer. The vane anemometer is structured as a wind mill that consists of multiple light, flat vanes that are mounted on a radial arm. The air forces acting on the vanes will cause the spindle to rotate at a rate depending on the air speed. Thus, the air speed/wind speed can be measured [14].

The ambient wind speed was measure from all four directions (north, south, east, west) and the average of the wind speed is considered.

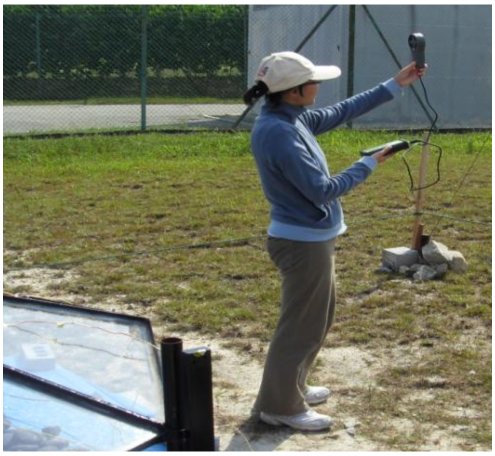


Figure 6.14: Measurement of the wind velocity at four different directions

The inlet air flow velocity into the system was measured from all the peripherals of the collector area to provide a more average data.

Figure 6.15: Measurement of velocity at inlet to the collector

By using the hot wire anemometer which has extendable length, one is able to capture the data at the centre of the canopy as well as the chimney inlet velocity.

Figure 6.16: Velocity measurement at chimney inlet

Figure 6.17: Velocity measurement at center of the canopy

7.3 SOLAR INTENSITY MEASUREMENT

The device used for measuring the total solar intensity at different location of the collector is known as the solarimeter.

Figure 6.18: Solar intensity measurement on site

7.4 EXPERIMENTAL PROCEDURE

The solar chimney model is placed in an open area whereby there is no obstruction to the air flow or solar radiation. A solid base made out of multiple concrete blocks and plywood provides reasonably good support to the whole model.

Experimental procedures for the test of variable height solar chimney is as stated below:-

1. Black painted rocks that were used as heat storage medium was spread across the base of the solar chimney model.

2. The height of the canopy is lowered until it is at 0.30m from the datum (model baseline).

3. The height of the solar chimney was set to be at 1.6 m, measuring from the top of the canopy.

4. Four thermocouple wires were attached to the collector (black painted rocks) located at the base of the model. The wires were attached to the collector rocks using layers of masking tape to assure that it will not come loose during any time of the experiment.

5. The rocks attached with the thermocouple wires were then placed at the periphery of the collector base.

6. Eight other thermocouple wires were then attached to the centre of each Perspex (canopy) piece using masking tape.

7. The data logger was turned on and the initial temperature data at 10am was recorded.

   Note: The other ends of the thermocouple wires which are already connected to the data logger’s chip will record the temperature of the measured surface once the data logger is turned on.

8. Using the solarimeter, the solar intensity measurement on site was taken and recorded.

9. Using the digital hot wire anemometer, the working fluid temperature and air flow velocity at the chimney inlet were taken.

10. Using the digital vane anemometer, measurements for the surrounding air velocity and collector inlet velocity were taken.

11. Step 7, 8, 9 and 10 were repeated at 12pm, 2pm and 4pm.

12. All data recorded are to be tabulated.

13. The experiment was repeated for canopy height 0.40m and 0.45 m.

14. Repeat the same experimental procedure for chimney height at 2.6 m and 3.6m.

    Note: All experiments are to be carried out for an average of three days for better data acquisition.

CHAPTER 8

RESULT AND DISCUSSION

8.1 MODEL

As of the model's design and dimensions, it is as mentioned at section 6.5 Final Model Design. The dimensions used are of a scale down measurement of the prototype in Manzanares.

Details of Manzanares:
Mean radius of collector = 122 m
Chimney height = 194.6 m

Details of Prototype:
Radius of collector = 1.05m
Chimney height = 1.67 m

For example:
Using ratio scaling;

$$\frac{Chimney\ height}{Collector\ mean\ radius} = \frac{194.6}{122} = \frac{H_C}{1.05}$$

$$H_c = 1.67\text{m}$$

The chimney is made up of two parts: 6in PVC pipe for turbine installation and 4in PVC pipe that is to be changed for the study of variable chimney height. The 6in pipe is of a length of 60cm from where the chimney joined with the canopy. Where else, the 4in pipe is to be changed out for every sets of variable chimney height (1m, 2m, 3m) experiments.

8.2 MATHEMATICAL MODEL

Using Microsoft Office Excel, the real ground temperature, T_g and canopy temperature are to be solved by utilizing all the mathematical relations as mentioned in the previous chapter as well as the primary estimation of ground temperature and canopy temperature data. The accomplished mathematical model is to be used for the experimental prototype and if proved successful, will be implemented on other upcoming solar chimney models.

Given the data of the Manzanares field as stated below [15]:-

Plant dimension	Weather radiation condition	Manzanares plant experimental test results
Rc = 122m hc = 1.85m Ht = 194.6m Rt = 5.08m	It = 1000W/m^2 Ta = 302K V_w = 5m/s	Δ T = 20K $V_{\text{chimeny inlet}}$ = 9m/s Tg = 70ºC

After inputting the data above into the validation model, the ground temperature estimated by the system is 341K (68 ºC). This showed that the model is able to provide a reasonable estimation of the ground temperature.

Using the validated program, the system is to produce estimated results of the ground temperature and canopy temperature which is to be compared with the experimental data collected from the fabricated model. From there, the results are to be analyzed and subject to further interpretation.

8.3 EXPERIMENTAL DATA

The experiments are conducted in 3 different chimney heights at 3 different canopy heights. The scenarios for the experiments are as mention below:-

a) At chimney height 1.6 m conduct experiments
   - At canopy height 0.30 m
   - At canopy height 0.40 m
   - At canopy height 0.45 m

b) At chimney height 2.6 m conduct experiments
   - At canopy height 0.30 m
   - At canopy height 0.40 m
   - At canopy height 0.45 m

c) At chimney height 3.6m conduct experiments
   - At canopy height 0.30 m
   - At canopy height 0.40 m
   - At canopy height 0.45 m

Note: Each experiment is to be conducted for 3 days and the result averaged

For comparison between the experimental and mathematical model, the chimney height of 1.60m is used.

At chimney height 1.60 m:

Table 8.1: Experimental and theoretical results of case study of 1.6m chimney height and 0.3m canopy height for 3 days.

Chimney Height 1.6 m								
Canopy height	Test	Time	I	T_f	T_g	T_c	Tg	Tc
30cm	1	12pm	420	35.3	49.5	40.8	51.5	38.7
		2pm	459	35.5	50.2	39.0	54.4	40.3
		4pm	314	36.7	45.4	37.7	46.3	36.3
	2	12pm	478	34.0	51.5	42.8	55.6	40.9
		2pm	500	39.7	55.4	43.3	54.8	40.2
		4pm	94.5	36.4	48.2	37.1	31.8	29.2
	3	12pm	308	35.2	44.4	38.4	45.9	36.3
		2pm	466	37.6	54.1	41.9	53.13	39.7
		4pm	410	37.0	52.5	43.7	50.76	38.5

Table 8.2: Experimental and theoretical results of case study of 1.6m chimney height and 0.4m canopy height for 3 days.

Chimney Height 1.6 m								
Canopy height	Test	Time	I	T_f	T_g	T_c	Tg	Tc
40cm	1	12pm	500	33.0	49.1	41.6	52.8	37.5
		2pm	512	38.9	51.6	45.4	55.1	38.6
		4pm	389	35.7	50.7	45.3	54.6	40.2
	2	12pm	473	33.7	48.4	43.6	55.5	39.0
		2pm	493	34.6	50.5	43.8	58.7	41.4
		4pm	200	34.0	45.8	35.2	40.4	32.8
	3	12pm	476	33.4	53.2	41.9	59.4	41.8
		2pm	490	35.2	52.0	44.5	56.3	40.1
		4pm	198	34.8	43.4	35.9	41.4	32.5

Table 8.3: Experimental and theoretical results of case study of 1.6m chimney height and 0.45m canopy height for 3 days.

Chimney Height 1.6 m								
Canopy height	Test	Time	I	T_f	T_g	T_c	Tg	Tc
45cm	1	12pm	340	35.2	48.0	40.6	48.1	36.0
		2pm	300	36.8	47.2	36.9	44.5	34.0
		4pm	198	35.3	43.9	35.0	38.5	31.5
	2	12pm	500	34.5	49.8	41.4	55.4	39.2
		2pm	493	37.0	52.5	43.8	56.0	39.6
		4pm	425	41.0	51.1	41.6	49.4	36.1
	3	12pm	485	34.0	50.7	43.6	55.3	39.0
		2pm	200	33.5	44.1	35.6	40.5	32.5
		4pm	290	36.9	46.2	38.1	43.7	33.8

Note: The highlighted data of Ground Temperature and Canopy Temperature are the theoretical result calculated using the program.

The theoretical data refers to the estimated data predicted by the mathematical model. By inputting the same details in terms of solar intensity, wind speed, collector air inlet velocity, chimney inlet velocity, emissivity and absorptivity of black painted rock, the program is to solve for the estimated ground and canopy temperature. From there on, the collector efficiency can be gauged. The theoretical data is to be compared with the experimental data of variable canopy height at chimney height of 1.6m.

Based on ref. [10], the emissivity and absorptivity of the black painted rock is:-
Emissivity, $\varepsilon_g = 0.95$
Absorptivity, $\alpha_g = 0.90$
Where else the emissivity and transitivity of the Perspex canopy is:-
Emissivity, $\varepsilon_c = 0.88$
Transmitivty, $\tau_c = 0.90$

These constants are to be inputted into the mathematical model before running the program.

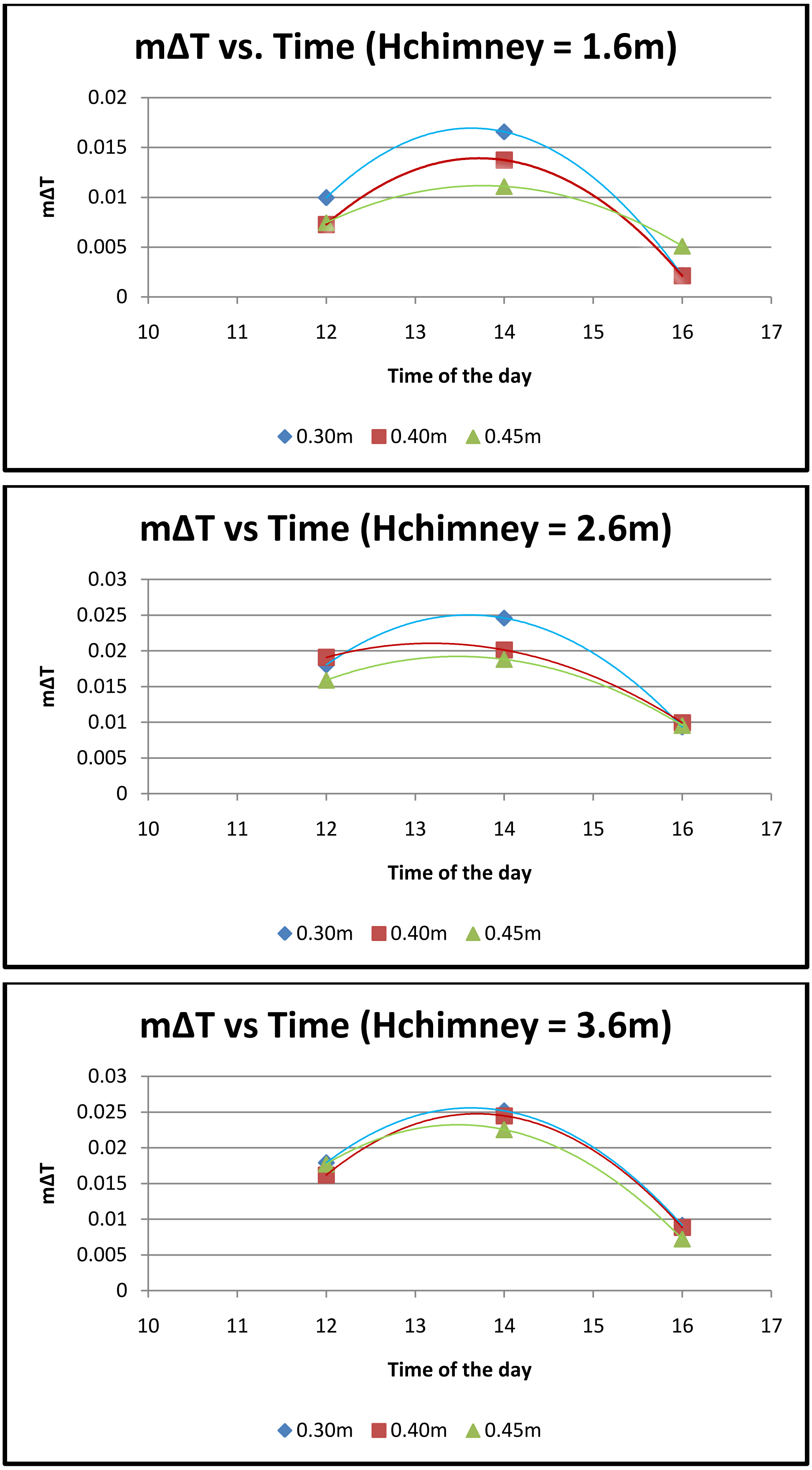


Figure 8.1: Experimental data of mΔT vs. Time of variable canopy height at chimney height 1.6m, 2.6m, 3.6m

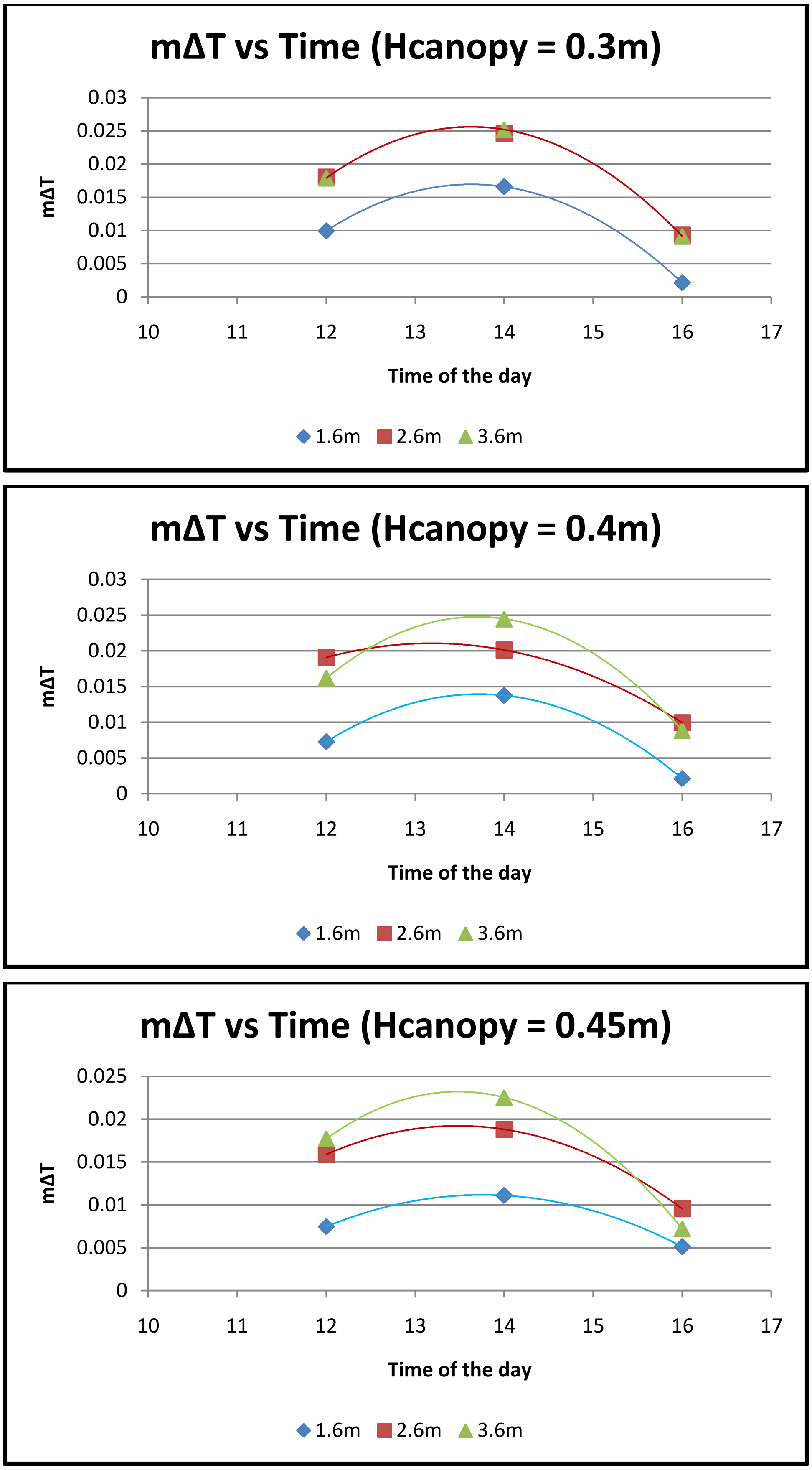


Figure 8.2: Experimental data of mΔT vs. Time of variable chimney height at canopy height 0.3m, 0.4m, 0.45m

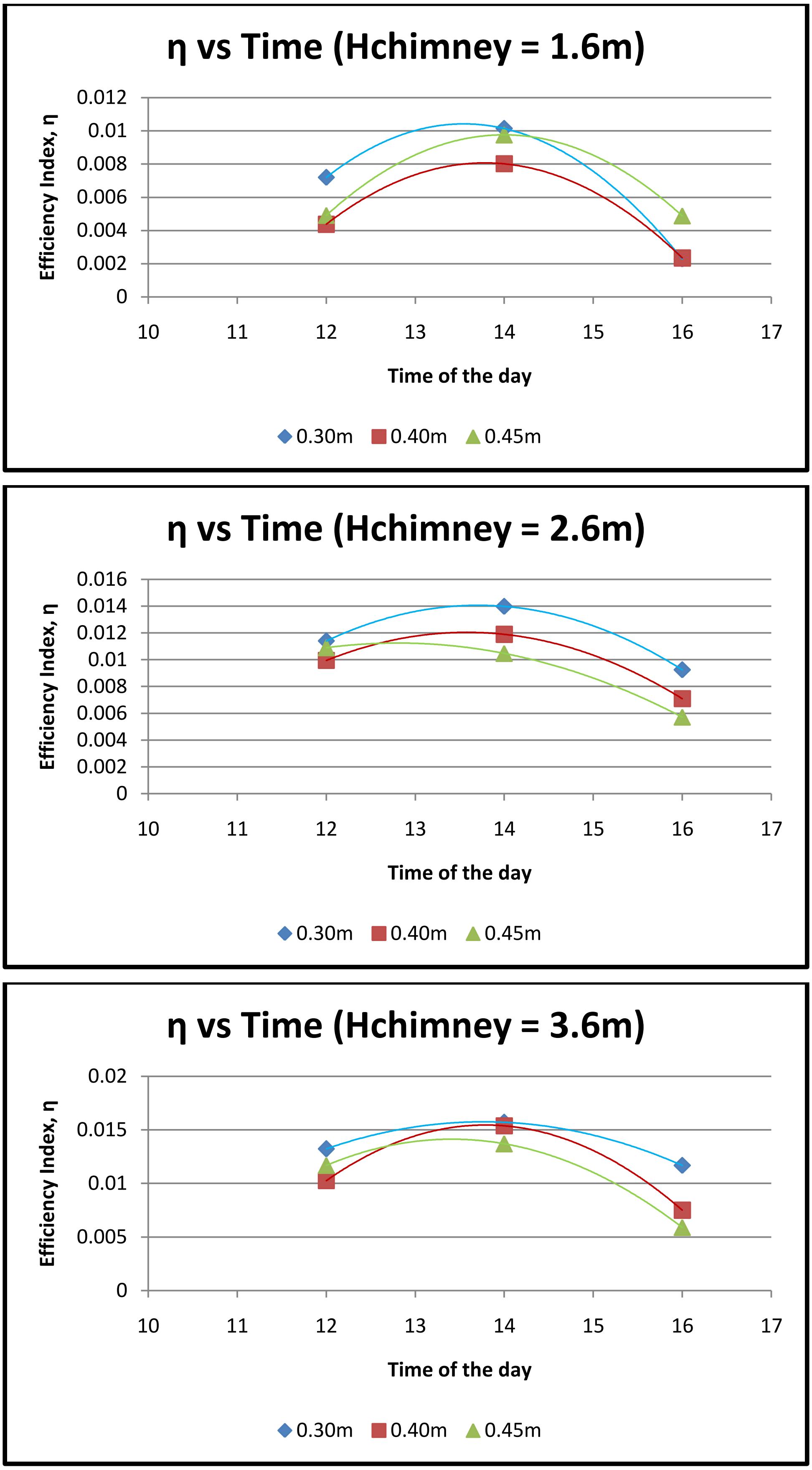


Figure 8.3: Experimental data of efficiency index, η vs. Time of variable canopy height at chimney height 1.6m, 2.6m 3.6m

8.4 DATA ANALYSIS

8.4.1 Comparison between Experimental and Theoretical Data

Referring to the tables 8.1, 8.2 and 8.3, it is noticeable that the predicted theoretical ground and canopy temperature (Tg and Tc) are fairly close to the experimental data with an exception of times when the solar radiation is of a small value (< 100).

This showed that the mathematical model is indeed able to predict the ground and canopy temperature given the similar environment conditions and parameters. Referring to the vast differences between the theoretical and experimental data during times of low solar intensity, multiple reasons could be the contributing factor to such a phenomenon.

Firstly, it could be contributed from the fast changing weather or during a cloudy day. Given the thought that a solar chimney is to be operated on a day-to-day basis, it is reasonable to take cloudy days into account as well. The ground and canopy are already well heated at a moment when the sun is out and the ground, canopy temperature recorded. Yet, due to fast changing weather, the cloud may have obscured the sun by the time the solar intensity data was taken. Thus, result in a set of data that portrays a high experimental data of ground and canopy temperature at times of low solar intensity.

Solar radiation changes could be drastic, however, due to the heat absorbtivity of ground collector (black painted rocks), the rocks could not adapt to the temperature change as quickly. The temperature recorded at one moment, is very much dependent on the environment parameters of previous hour.

8.4.2 Effect of Canopy Height

The experimental results of the effect of canopy height (Hcanopy) can be seen as shown in Figures 8.1, 8.2 and 8.3. These figures showed that the hourly variation of the performance parameter and its efficiency at 12 midday, 2pm and 4pm.

$m\Delta T$ depicts the collector performance where else the efficiency term refers to the whole of the system.

Referring to Figure 8.1, 8.2 and 8.3, it is obvious that at canopy height 0.30m, the collector performance and system efficiency is of the highest value as compared to data for canopy height 0.40m and 0.45m. The result acquire is reasonable and acceptable based on logic of inertia forces. Looking at the system of solar chimney itself, regardless of the heat transfer mechanism, there are two natural forces involved: Buoyancy force and inertia force. Buoyancy force is one that is responsible for the updraft of air due to difference in pressure along the chimney. Where else, inertia force is involved when the surrounding cooler wind blew pass and forces the hotter and lighter air out from below the canopy of the solar chimney. Therefore, result in cooler air to occupy the spaces in between the canopy cover and ground collector.

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

The results acquired are also justified by previous researcher Miss Aseel Khaliel Shyia [6]. In her thesis for her research ‘Parametric Study of Solar Chimney Performance’, her results showed that at lower canopy height, the better system performance.

8.4.3 Effect of Chimney Height

Referring to Figure 8.2 and 8.3, the collector performance and system efficiency is better when the chimney height is 3.6m as compared to the lower chimney height 1.6m and 2.6m. This is because at a higher chimney height, the difference in pressure along the chimney is larger, and thus encourages wind updraft and that leads to the higher efficiency of the system.

8.4.4 Best Time for the Efficient System

Results shows that majority at 2pm is the preferable time for the system to work at the highest efficiency, mainly because of the higher value of solar intensity.

CHAPTER 9

CONCLUSION & RECOMMENDATIONS

9.1 CONCLUSION

The experimental and theoretical results acquired and presented through the modeling of the solar chimney, have shown to be able to provide a base line analysis of the collector performance and overall system efficiency.

The following can be concluded from the case studies completed:

1. Based on the Manzanares plant data, the mathematical model developed was validated.
2. Results obtained from the mathematical model were found to have fairly good agreement with the experimental results of the solar chimney model.
3. The product of m x ΔT is the main parameter that depicts the performance of the collector.
4. The best system performance of the solar chimney model is when the canopy height is of 0.30m at a collector radius of 1.05m
5. The system shown the best efficiency at the case study when the chimney height is 3.6m and the canopy height is 0.30m

9.2 RECOMMENDATIONS

Based on the results, the following are some of the recommendations for developing a more efficient solar chimney model:

1. Allow extension of larger collector radius and study the effect of it towards the performance
2. For better streamlining of working fluid, sharp ends at chimney inlet should be avoided.
3. Material changed for canopy; instead of using Perspex which its properties and transmittivity may deteriorate throughout the years, glass or fiberglass could be considered as a substitute.
4. Study of canopy angle inclination from 10º, 20º to 45º and its effect on the

system performance should be considered

v. The study of the model incorporated with the usage of wind turbine.
vi. Improvements of the Mathematical model in terms of including the study of variable chimney height effect on the system performance.

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APPENDICES

At chimney height = 1.6m

Canopy height = 0.3m

Time	A chimney	Density	V chim	T fluid	I	T diff	m T	Efficiency
12	0.0186289	1.0335	0.42	34.83	402	1.23	0.009946	0.007199
14	0.0186289	1.0335	0.43	37.6	475	2	0.016558	0.010143
16	0.0186289	1.0335	0.37	36.7	272.8	0.3	0.002137	0.00228

Table 1: Experimental result of case study 1.6m chimney height and 0.30m canopy height

Canopy height = 0.4m

Time	A chimney	Density	V chim	T fluid	I	T diff	mT	Efficiency
12	0.0186289	1.0335	0.29	33.4	483	1.3	0.007258	0.004373
14	0.0186289	1.0335	0.31	36.2	498.3	2.3	0.013727	0.008016
16	0.0186289	1.0335	0.15	34.83	262.3	0.73	0.002108	0.002339

Table 2: Experimental result of case study 1.6m chimney height and 0.40m canopy height

Canopy height = 0.45m

Time	A chimney	Density	V chim	T fluid	I	T diff	mT	Efficiency
12	0.0186289	1.0335	0.43	34.6	441.7	0.9	0.007451	0.004909
14	0.0186289	1.0335	0.32	35.8	331	1.8	0.01109	0.009749
16	0.0186289	1.0335	0.53	37.3	304.3	0.5	0.005102	0.004879

Table 3: Experimental result of case study 1.6m chimney height and 0.45m canopy height

At chimney height = 2.6m

Canopy height = 0.3m

Time	A chimney	Density	V chim	T fluid	I	T diff	mT	Efficiency
12	0.0186289	1.0335	0.461	36.53	460	2.03	0.018018	0.011398
14	0.0186289	1.0335	0.58	38.4	511.3	2.2	0.024567	0.013981
16	0.0186289	1.0335	0.604	36.6	292.7	0.8	0.009303	0.009249

Table 4: Experimental result of case study 2.6m chimney height and 0.30m canopy height

Canopy height = 0.4m

Time	A chimney	Density	V chim	T fluid	I	T diff	mT	Efficiency
12	0.0186289	1.0335	0.472	35.5	558.7	2.1	0.019084	0.009939
14	0.0186289	1.0335	0.387	37.3	492.3	2.7	0.020117	0.011891
16	0.0186289	1.0335	0.456	39.03	407	1.13	0.009921	0.007093

Table 5: Experimental result of case study 2.6m chimney height and 0.40m canopy height

Canopy height = 0.45m

Time	A chimney	Density	V chim	T fluid	I	T diff	mT	Efficiency
12	0.0186289	1.0335	0.55	34.5	424.3	1.5	0.015884	0.010893
14	0.0186289	1.0335	0.465	35.9	522.7	2.1	0.018801	0.010466
16	0.0186289	1.0335	0.62	36.4	486	0.8	0.009549	0.005718

Table 6: Experimental result of case study 2.6m chimney height and 0.45m canopy height

<u>At chimney height = 3.6m</u>

Canopy height = 0.3m

Time	A chimney	Density	V chim	T fluid	I	T diff	mT	Efficiency
12	0.0186289	1.0335	0.489	35.9	393.7	1.9	0.017888	0.013221
14	0.0186289	1.0335	0.561	37.53	466.7	2.33	0.025166	0.015691
16	0.0186289	1.0335	0.65	38.23	227.67	0.73	0.009136	0.011676

Table 7: Experimental result of case study 3.6m chimney height and 0.30m canopy height

Canopy height = 0.4m

Time	A chimney	Density	V chim	T fluid	I	T diff	mT	Efficiency
12	0.0186289	1.0335	0.56	36.6	459	1.5	0.016173	0.010253
14	0.0186289	1.0335	0.605	37.1	463	2.1	0.024461	0.015373
16	0.0186289	1.0335	0.656	38	342.7	0.7	0.008841	0.007507

Table 8: Experimental result of case study 3.6m chimney height and 0.40m canopy height

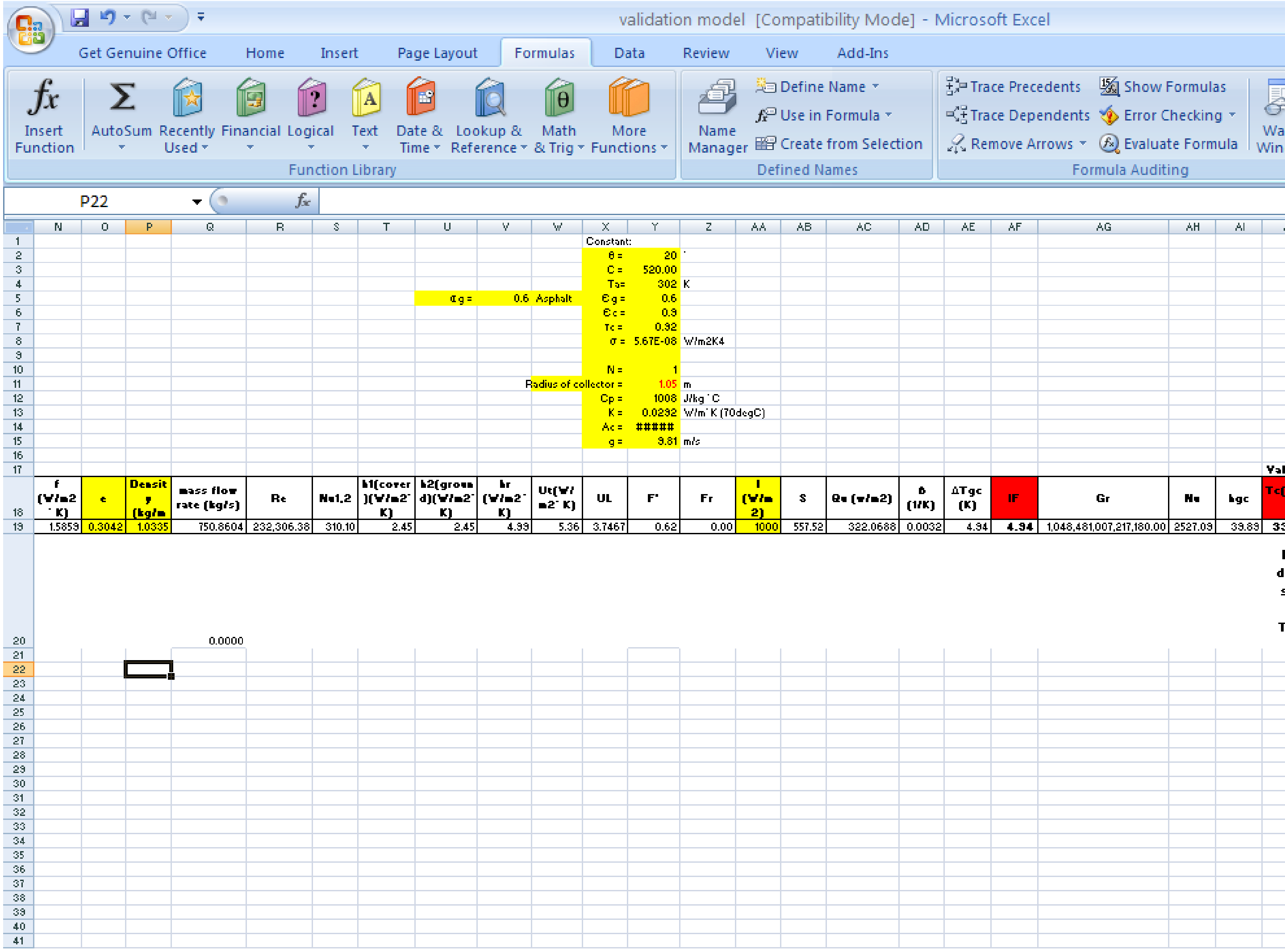
Canopy height = 0.45m

Time	A chimney	Density	V chim	T fluid	I	T diff	mT	Efficiency
12	0.0186289	1.0335	0.657	35.7	441.3	1.4	0.017709	0.011677
14	0.0186289	1.0335	0.65	41.2	478.7	1.8	0.022526	0.013693
16	0.0186289	1.0335	0.75	35.5	356.7	0.5	0.00722	0.00589

Table 9: Experimental result of case study 3.6m chimney height and 0.45m canopy height

Note:

Parameters such as Chimney inlet velocity (Vchim), working fluid temperature (Tfluid), Solar radiation (I) are averaged value of 3 days of experiments.



Constant:
θ = 20 ˚
C = 520.00
Ta= 302 K
αg = 0.6 Asphalt
εg = 0.6
εc = 0.9
τc = 0.92
σ = 5.67E-08 W/m2K4
N = 1
Radius of collector = 1.05 m
Cp = 1008 J/kg ˚C
K = 0.0292 W/m˚K (70degC)
Ac = #####
g = 9.81 m/s

f (W/m2˚K)	e	Density (kg/m	mass flow rate (kg/s)	Re	Nu1,2	h1(cover)(W/m2˚K)	h2(ground)(W/m2˚K)	hr (W/m2˚K)	Ut(W/m2˚K)	UL	F'	Fr	I (W/m2)	S	Qu (w/m2)	β (1/K)	ΔTgc (K)	IF	Gr	Nu	hgc
1.5859	0.3042	1.0335	750.8604	232,306.38	310.10	2.45	2.45	4.99	5.36	3.7467	0.62	0.00	1000	557.52	322.0688	0.0032	4.94	**4.94**	1,048,481,007,217,180.00	2527.09	39.89

0.0000

Example of Microsoft Office Excel Validation Model Worksheet