A STUDY OF SOLAR CHIMNEY PERFORMANCE USING FLUENT SOFTWARE

By

Azman Bin Daud

Dissertation submitted in partial fulfillment of

the requirements for the

Bachelor of Engineering (Hons)

(Mechanical Engineering)

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CERTIFICATION OF APPROVAL

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Approved by,

____
(Ms. Chin Yee Sing)

UNIVERSITI TEKNOLOGI PETRONAS
TRONOH, PERAK
December 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.

(AZMAN BIN DAUD)

ABSTRACT

A solar chimney is a solar power plant which generates mechanical energy (usually in terms of turbine shaft work) from the hot rising air that is heated by solar energy. This project is a study of Solar Chimney performance using FLUENT software. Computational Fluid Dynamic (CFD) modeling techniques were used to assess the impact of canopy height ($h_{c)}$ and the tower height (h_t) to the performance of the solar chimney. Due to time constraint, the simulation only proceeds with variable of canopy height (h_c) and tower height (h_t). This report consist of 5 chapters; introduction, literature review, methodology, results and discussions. The method for the simulation basically involved 3 steps which are pre-processing, solving and post-processing. The operating conditions which includes in the simulation are taken from the experimental works. The results from the simulation which are air velocity at chimney inlet (V_{in}) and fluid temperature (T_{fluid}) are then used in the calculation of collector performance ($\dot{m}\Delta T$) and system efficiency (η). The results showed that the highest collector performance and system efficiency is when the canopy height (h_c) and chimney height (h_t) was set at 0.2m and 2.6m respectively.

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLE

NOMENCLATURES

Θ	Canopy slope angle (^{o})
h_c	Canopy height (m)
h_t	Chimney tower height (m)
R_c	Radius of chimney (m)
R_g	Radius of ground/collector (m)
H_t	Total chimney height (m)
D_g	Ground diameter (m)
D_t	Chimney tower diameter (m)
v_{in}	Air velocity at chimney inlet (m/s)
v_{out}	Air velocity at outlet (m/s)
v_{tower}	Air velocity at chimney tower (m/s)
$T_{ambient}$	Ambient temperature (K)
T_{ground}	Ground temperature (K)
T_{canopy}	Canopy temperature (K)
T_{fluid}	Fluid temperature at chimney inlet (K or ^{o}C)
T_{in}	Inlet temperature (K)
V_{wind}	Wind velocity (m/s)
$V_{in\ collector}$	Air velocity at collector inlet (m/s)
V_f	Fluid velocity (m/s)
$\dot{m}$	Mass flow rate (kg/s)
ΔT	Temperature difference ($T_{fluid} - T_{ambient}$)
ρ_{air}	Density of air (kg/m^3)
I	Solar Radiation intensity (W/m^2)
C_p	Specific Heat (J/kg.^{o}C)
A_c	Cross sectional area at any point from inlet to exit of the chimney (m^2)
η_c	Collector efficiency

ABBREVIATIONS

CFD	Computational Fluid Dynamics
GAMBIT	Geometry And Mesh Building Intelligent Toolkit
UTP	Universiti Teknologi PETRONAS
PVC	Polyvinylchloride
2ddp	Two dimension double precision

CHAPTER 1

INTRODUCTION

1.1 Project background

With the fossil energy is nearing exhaustion as well as green-house effect and air pollution being more severe to the human being, the utilization of renewable energy technologies are increasingly gaining great importance. Solar energy is clean and a form of renewable energy resource which utilizing will not produce green-house gases or hazardous wastes.

Of many techniques utilizing solar energy, solar chimney seems to be the most attractive. The concept was designed and put into use by J. Schaich and colleagues during the 1980s [1, 2]. It works on the principle that the wind turbine could be driven by air flow caused by stack effect inside the solar chimney, owing to the heating process in the solar hot air collector [3].

Solar chimney works on the simple principle that hot air rises. When the sun rays impinges on the roof or canopy, the solar energy radiated from the sun will be absorb at the wall surface and the air in the chimney is then heated by conduction and radiation. The air will become less dense and will rise. The current of the rising warm air drive the turbine and the turbine that is set at the base of the chimney will drives the electrical generator to produce electricity.

A typical solar chimney is consisting of three (3) main components which are the solar collector, the chimney and the turbine. The mini prototype of the solar chimney in UTP shown in Figure 2 does not have a turbine because the project focuses on study about the air flow inside the solar chimney and the addition of turbine will be the future work in UTP.

The study of solar chimney performance using FLUENT software is basically a project which simulates the solar chimney by using the Computational Fluid Dynamics (CFD) technique and FLUENT software as the solver to do the calculations and obtain the air velocity (v_{in}) and temperature at (T_{fluid}) chimney inlet.

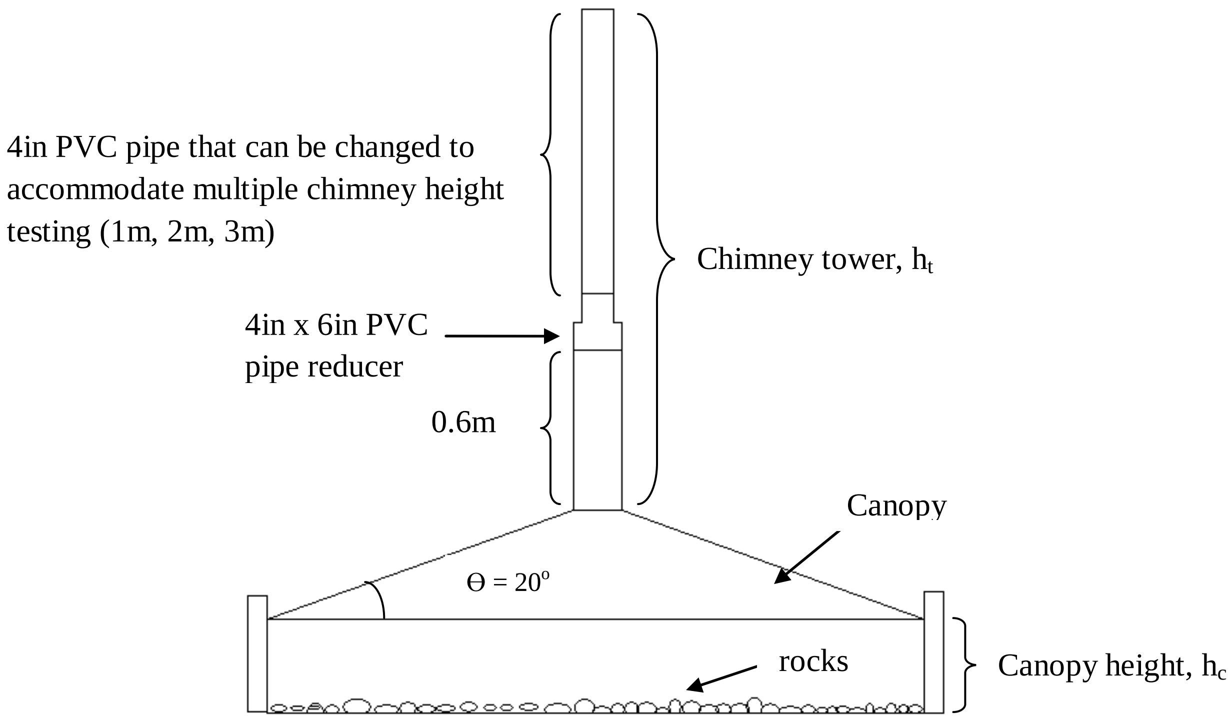


Figure 1: Sketch of mini solar chimney in UTP

Figure 2: Mini solar chimney in UTP

1.2 Problem Statement

The usage of solar chimney as a source of renewable energy is a possible solution to curb the depletion of fossil fuel problem. Therefore, a study of solar chimney performance using FLUENT software is necessary and the simulation results can be compared with experimental results by [6].

1.3 Objectives and Scope of Study

1.3.1 Objective

To study the effects of canopy height (h_c) and tower height (h_t) on the performance of a solar chimney.

1.3.2 Scope of Study

In this research, the main objective is to investigate the relationship between the variable canopy heights (h_c) and tower height (h_t) of solar chimney towards its performance. The scopes of study involved in this research are:-

a. Study the basics of solar chimney

b. Gather all information, data and dimension from co-supervisor and his student about their experimental work on mini solar solar chimney in UTP.

c. Learn and familiarize the GAMBIT and FLUENT software and simulate the solar chimney in 2-D.

d. Run the simulation using different variables which are canopy height ($h_{c)}$ and tower height (h_t) and obtain the air velocity (v_{in}) and fluid temperature (T_{fluid}) at chimney inlet.

e. Interpret the results.

CHAPTER 2

LITERATURE REVIEW

Even though the technology involved in constructing a solar chimney plant is simple, many aspects need to be considered before the plant can be designed for an optimal performance. Previous researches have studied on the performance effect of solar chimney and tried to develop experimental method and mathematical model for understanding air flow behavior and temperature distribution inside solar chimney. The following summaries can be listed:

The study of [2], showed that an increase of the collector radius increased output power but reduced plant efficiency. On the other hand, efficiency increased with the tower height, and mass flow velocity increased with the tower radius while the flow velocity remained constant.

In a study conduct by [3], the capacity of power generation is dependent on solar irradiance, ambient temperature, etc. Also important for system performance is solar chimney height, collector efficiency, turbine efficiency and surface roughness inside the chimney. Under given condition, the power generation capacity increases as the solar chimney height and solar collector area is increased. It is also found that the higher the solar irradiance, the higher the efficiencies of the components and the greater the power generation will be.

Detailed theoretical preliminary research and a wide range of wind tunnel experiments leads to the establishment of an experimental plant with a peak output of 50 kW on a site made available by the Spanish utility Union Electrica Fenosa in Manzanares (about 150 km south of Madrid) in 1981/82. The prototype of the solar tower plant at Manzanares is shown in Figure 3. The objective was to verify, through field measurements, the performance projected from calculations based on theory, and to examine the influence of individual components on the plant’s output and efficiency under realistic engineering and meteorological conditions [4].

Using the Spanish prototype as model, [5] concluded that the pressure throughout the system is negative value. The temperature difference between inlet and outlet of collector, as well as the differential pressure of collector-chimney transition section, is increasing with the increase in solar radiation intensity. The calculated results are approximately equivalent to the relative experimental data of the Spanish Prototype.

Based on research by [6], the mathematical model developed based on the Manzanares plant data was validated. The results obtained from the mathematical model were found to have fairly good agreement with the experimental results of the solar chimney model. The product of mass flow rate ($\dot{m}$) times (x) temperature difference (ΔT) is the main parameter that depicts the performance of the collector. 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. The system show the highest efficiency at the case study when the chimney height is 3.6m and the canopy height is 0.30m. The results from this research is taken as a comparison to the simulation results of solar chimney performance using FLUENT software in this project.

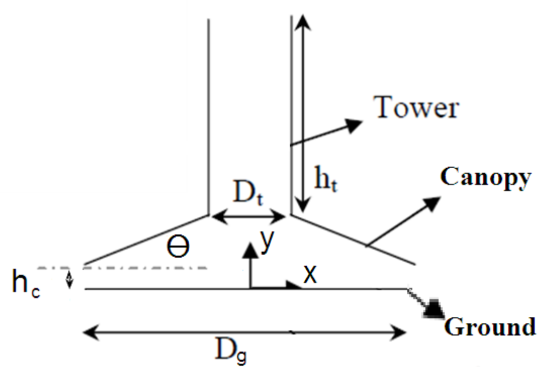


Figure 3: Schematic view of solar chimney system

Since the mini prototype of the solar chimney model is axisymmetric structure, 2-D cylindrical coordinate system is used. This is based on the research by [7], which consider the solar updraft tower or solar chimney systems in the cylindrical coordinate (see Figure 3), because the system is symmetric relative to Y axis and with good approximation, it can be considered as 2-D flow in x-y direction.

CHAPTER 3

METHODOLOGY

The methodology used in this study mainly involved in CFD simulation. FLUENT and GAMBIT are chosen as the suitable tools to simulate the air flow and temperature distribution in the solar chimney model.

3.1 Analysis technique

On the simulation works, there are three (3) general stages taken. The first stage is the pre-processing stage in which GAMBIT is used to create the solar chimney geometry in 2-D and mesh models for CFD. After the first stage has been done, the second stage or the solving step is reached. During this stage, simulation will be performed using commercial software, FLUENT. Lastly, the post-processing step will take place where the result from FLUENT simulation will be examined and interpreted.

3.1.1 Geometric model and Gridding means (GAMBIT)

The 2-D model of the solar chimney was built in GAMBIT, which is a pre-processor of FLUENT. The grid was also generated in GAMBIT. The mini solar chimney in UTP is the prototype of this geometric model. In the model, the collector or the canopy diameter is fixed at 2.1m, the chimney tower is 1.6m (varies at 2.6m and 3.6m) and the canopy angle is fixed 20^{o}. Since the model is symmetrical in all directions, only half of the geometry was created in GAMBIT. The simplification have been made where the diameter reduction of the mini solar chimney tower has been neglected.

Geometric scale:

Referring to Figure 4, the canopy height, AB which represents h_c, is 0.3m. The height of chimney tower, CD which represents h_t, is 1.6m and the radius of chimney, DE which represents R_c is 7.62cm. The total chimney height EF (H_t) is

2.25m. The ground radius, AF which represents R_g is 1.05m. Θ is the canopy slope angle which is 20^o.

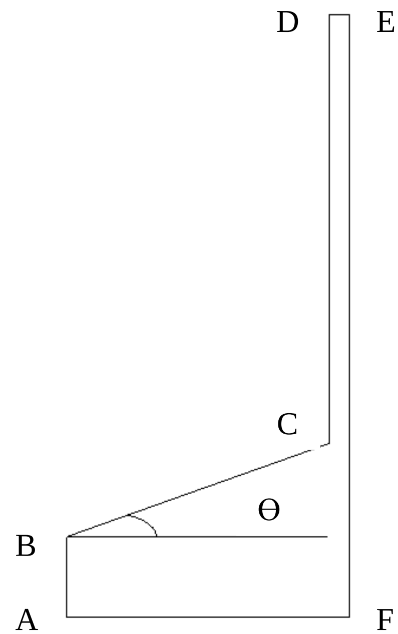


Figure 4: Schematic of solar chimney model

Mesh creations:

Since the geometry of the solar chimney is in 2-D, the mesh generation involved only faces. The geometry that has been created only has one face. A Quad with Pave type mesh was used with the interval size was set as 1.

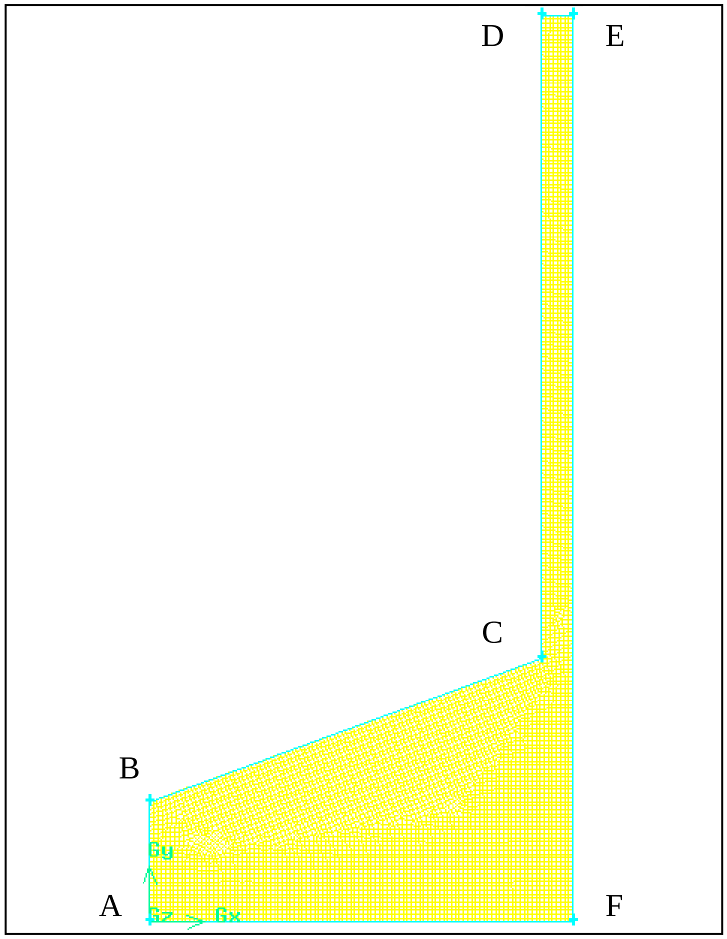


Figure 5: Mesh for the solar chimney geometry for canopy height 0.3m and tower height 1.6m

Boundary condition:

AB and DE can be considered as velocity inlet and pressure outlet boundary respectively. EF is an asymmetric. While other boundaries in Figure 4 are wall boundary. Computation of natural convection was carried out by the momentum equation which is caused by the change of density. Boussinesq model was used here since the temperature difference in the system is small.

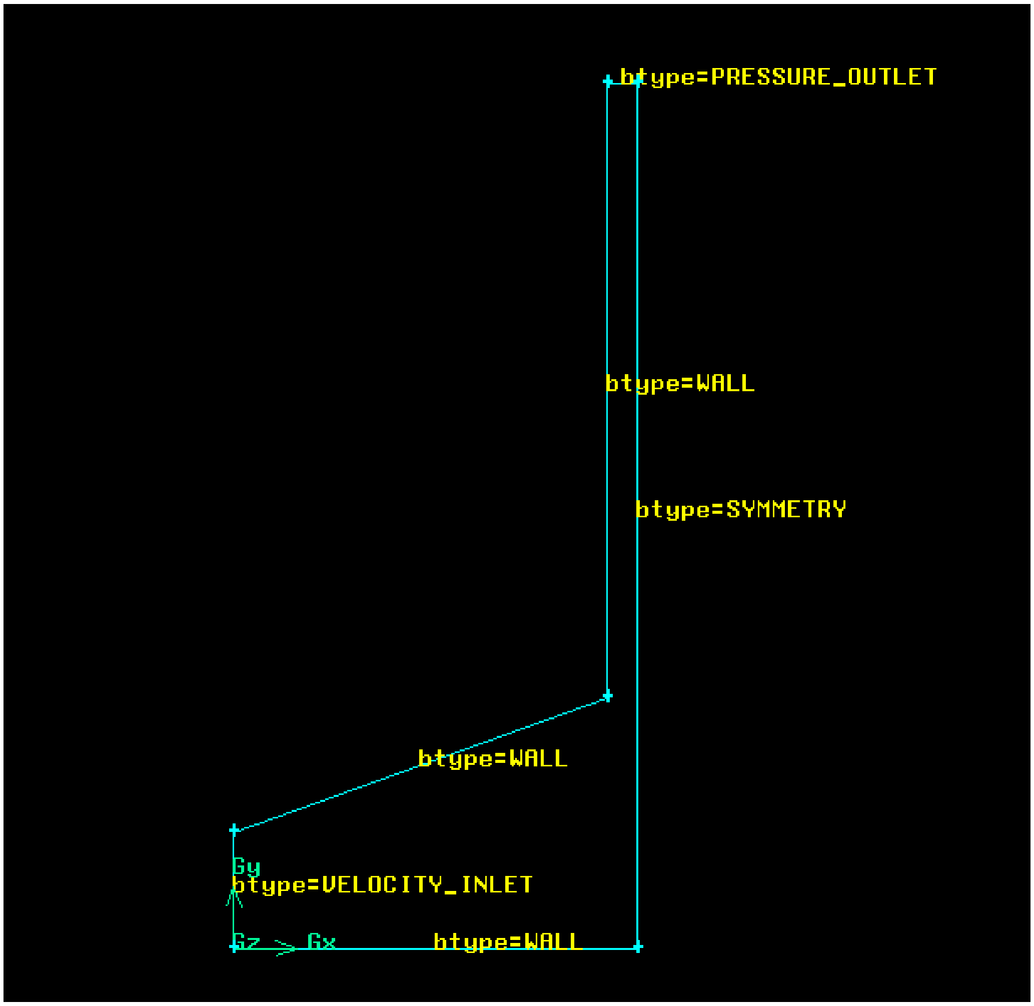


Figure 6: Boundary condition for the Solar Chimney model

3.1.2 Discretization (FLUENT)

Before the simulation starts in FLUENT, the "2ddp" option is used to select the two-dimensional, double precision solver. In the double precision solver, each floating point number is represented using 64 bits in contrast to the single-precision solver which uses 32 bits. The extra bits increase not only the precision but also the range of magnitudes that can be represented. However, the downside of using double precision is that it requires more memory.

The model uses a pressure based solver with implicit formulation. The momentum, continuity and energy equation are solved using the second order upwind. Reynolds number from the experimental works [6] suggests the flow is in the turbulent regime, therefore a standard k-epsilon with Realizable model is used for the turbulence modeling with the turbulence equations being solved using the second order upwind scheme. This Realizable k-epsilon model is able to produces more accurate results for boundary layer flows than the Standard k-epsilon model. In addition, Enhanced Wall Treatment is chosen in order to deals with the resolution of the boundary layer in the model.

P1 radiation model is used for heat transfer simulation to study the effect of heating or cooling of surface due to radiation. P-1 model assumes that all surfaces are diffuse. This means that the reflection of incident radiation at the surface is isotropic with respect to the solid angle. The implementation assumes gray radiation. [11]

3.1.3 CFD Simulation

Under present study, commercial code FLUENT 6.3.26 was used. Few assumptions were made in the CFD model based on the experimental work that has been done.

i. The gas behaves as an ideal gas.
ii. The system is steady.
iii. Air inlet temperature, T_{in} is equal to ambient temperature, $T_{ambient}$
iv. The thickness of the Perspex is uniform throughout.
v. Inclination angle of canopy has no significant impact on the top loss coefficient.
vi. The variation of temperature is so small that change in viscosity and thermal conductivity is negligible.
vii. The ground surface is assumed to be a smooth surface.
viii. Diameter reduction at mini solar chimney tower is neglected.

Table 1: Solid parameters used in the simulation

Solid		
Perspex	Density (kg/m^3)	1190
	Specific heat (J/kg-K)	1460
	Thermal Conductivity (w/m-K)	0.189
	Emissivity, ε_c	0.88
PVC	Density (kg/m^3)	1390
	Specific heat (J/kg-K)	1050
	Thermal Conductivity (w/m-K)	0.21
Rock	Density (kg/m^3)	2240
	Specific heat (J/kg-K)	800
	Thermal Conductivity (w/m-K)	4.0
	Emissivity, ε_g	0.90

The simulation work can be further divide into three different cases:

- **Case 1**: At chimney height = 1.6m

  Variation in the canopy height:

  a) 0.3m
  b) 0.4m
  c) 0.45m

- **Case 2**: At chimney height = 2.6m

  Variation in the canopy height:

  a) 0.3m
  b) 0.4m
  c) 0.45m

- **Case 3**: At chimney height = 3.6m

  Variation in the canopy height:

  a) 0.3m
  b) 0.4m
  c) 0.45m

Each of the simulation will be done using different canopy temperature (T_{canopy}), ground temperature (T_{ground}), ambient temperature ($T_{ambient}$), collector/canopy inlet velocity ($V_{in\ collector}$) and solar intensity (I) according to certain time in a day which are 12noon, 1400 and 1600. These values are taken from the average values of 3 days' experiment. The properties of air used in the simulation are based on the ambient temperature which is different on 12noon, 1400 and 1600.

*** Note: The highlighted data are obtained previously by experiment.**

Case 1 a: Chimney height = 1.6m

Canopy height = 30cm

Chimney height = 1.6m	
Canopy height = 30cm	
Time= 12noon	
T_{canopy} (^oC)	40.67
T_{ground} (^oC)	48.5
$T_{ambient}$ (^oC)	33.6
$V_{in\ collector}$ (m/s)	0.583
I (W/m^2)	402
ρ (kg/m^3)	1.152
C_p ($J/kg.^oC$)	1005

Chimney height = 1.6m	
Canopy height = 30cm	
Time= 1400	
T_{canopy} (^oC)	41.44
T_{ground} (^oC)	53.22
$T_{ambient}$ (^oC)	35.6
$V_{in\ collector}$ (m/s)	0.633
I (W/m^2)	475
ρ (kg/m^3)	1.144
C_p ($J/kg.^oC$)	1005

Chimney height = 1.6m	
Canopy height = 30cm	
Time= 1600	
T_{canopy} (^oC)	39.5
T_{ground} (^oC)	48.68
$T_{ambient}$ (^oC)	36.4
$V_{in\ collector}$ (m/s)	0.417
I (W/m^2)	272.8
ρ (kg/m^3)	1.141
C_p ($J/kg.^oC$)	1005

Case 1 b: Chimney height = 1.6m

Canopy height = 40cm

Chimney height = 1.6m	
Canopy height = 40cm	
Time= 12noon	
T_{canopy} (^oC)	42.4
T_{ground} (^oC)	50.24
$T_{ambient}$ (^oC)	32.1
$V_{in\ collector}$ (m/s)	0.479
I (W/m^2)	483
ρ (kg/m^3)	1.158
C_p ($J/kg.^oC$)	1005

Chimney height = 1.6m	
Canopy height = 40cm	
Time= 1400	
T_{canopy} (^oC)	44.6
T_{ground} (^oC)	51.46
$T_{ambient}$ (^oC)	33.9
$V_{in\ collector}$ (m/s)	0.559
I (W/m^2)	498.3
ρ (kg/m^3)	1.151
C_p ($J/kg.^oC$)	1005

Chimney height = 1.6m	
Canopy height = 40cm	
Time= 1600	
T_{canopy} (^oC)	38.79
T_{ground} (^oC)	46.63
$T_{ambient}$ (^oC)	34.1
$V_{in\ collector}$ (m/s)	0.530
I (W/m^2)	262.3
ρ (kg/m^3)	1.150
C_p ($J/kg.^oC$)	1005

Case 1 c: Chimney height = 1.6m

Canopy height = 45cm

Chimney height = 1.6m	
Canopy height = 45cm	
Time= 12noon	
T_{canopy} (^oC)	41.86
T_{ground} (^oC)	49.49
$T_{ambient}$ (^oC)	33.7
$V_{in\ collector}$ (m/s)	0.215
I (W/m^2)	441.7
ρ (kg/m^3)	1.152
C_p (J/kg.^oC)	1005

Chimney height = 1.6m	
Canopy height = 45cm	
Time= 1400	
T_{canopy} (^oC)	38.77
T_{ground} (^oC)	47.93
$T_{ambient}$ (^oC)	34.0
$V_{in\ collector}$ (m/s)	0.752
I (W/m^2)	331
ρ (kg/m^3)	1.162
C_p (J/kg.^oC)	1005

Chimney height = 1.6m	
Canopy height = 45cm	
Time= 1600	
T_{canopy} (^oC)	38.92
T_{ground} (^oC)	47.07
$T_{ambient}$ (^oC)	36.8
$V_{in\ collector}$ (m/s)	0.348
I (W/m^2)	304.3
ρ (kg/m^3)	1.139
C_p (J/kg.^oC)	1005

Case 2 a: Chimney height = 2.6m

Canopy height = 30cm

Chimney height = 2.6m	
Canopy height = 30cm	
Time= 12noon	
T_{canopy} (^oC)	42.41
T_{ground} (^oC)	51.0
$T_{ambient}$ (^oC)	34.5
$V_{in\ collector}$ (m/s)	0.601
I (W/m^2)	460
ρ (kg/m^3)	1.148
C_p (J/kg.^oC)	1005

Chimney height = 2.6m	
Canopy height = 30cm	
Time= 1400	
T_{canopy} (^oC)	42.18
T_{ground} (^oC)	53.4
$T_{ambient}$ (^oC)	36.2
$V_{in\ collector}$ (m/s)	0.627
I (W/m^2)	511.3
ρ (kg/m^3)	1.142
C_p (J/kg.^oC)	1005

Chimney height = 2.6m	
Canopy height = 30cm	
Time= 1600	
T_{canopy} (^oC)	39.75
T_{ground} (^oC)	47.38
$T_{ambient}$ (^oC)	35.8
$V_{in\ collector}$ (m/s)	1.003
I (W/m^2)	292.7
ρ (kg/m^3)	1.143
C_p (J/kg.^oC)	1005

Case 2 b: Chimney height = 2.6m

Canopy height = 40cm

Chimney height = 2.6m	
Canopy height = 40cm	
Time= 12noon	
T_{canopy} (^oC)	41.72
T_{ground} (^oC)	51.49
$T_{ambient}$ (^oC)	37.9
$V_{in\ collector}$ (m/s)	0.692
I (W/m^2)	558.7
ρ (kg/m^3)	1.135
C_p (J/kg.^oC)	1005

Chimney height = 2.6m	
Canopy height = 40cm	
Time= 1400	
T_{canopy} (^oC)	44.13
T_{ground} (^oC)	55.07
$T_{ambient}$ (^oC)	34.6
$V_{in\ collector}$ (m/s)	1.163
I (W/m^2)	492.3
ρ (kg/m^3)	1.148
C_p (J/kg.^oC)	1005

Chimney height = 2.6m	
Canopy height = 40cm	
Time= 1600	
T_{canopy} (^oC)	40.53
T_{ground} (^oC)	49
$T_{ambient}$ (^oC)	37.9
$V_{in\ collector}$ (m/s)	0.717
I (W/m^2)	407
ρ (kg/m^3)	1.135
C_p (J/kg.^oC)	1005

Case 2 c: Chimney height = 2.6m

Canopy height = 45cm

Chimney height = 2.6m	
Canopy height = 45cm	
Time= 12noon	
T_{canopy} (^oC)	37.9
T_{ground} (^oC)	45.83
$T_{ambient}$ (^oC)	33
$V_{in\ collector}$ (m/s)	0.26
I (W/m^2)	424.3
ρ (kg/m^3)	1.154
C_p (J/kg.^oC)	1005

Chimney height = 2.6m	
Canopy height = 45cm	
Time= 1400	
T_{canopy} (^oC)	41.62
T_{ground} (^oC)	53.22
$T_{ambient}$ (^oC)	33.8
$V_{in\ collector}$ (m/s)	0.95
I (W/m^2)	522.7
ρ (kg/m^3)	1.151
C_p (J/kg.^oC)	1005

Chimney height = 2.6m	
Canopy height = 45cm	
Time= 1600	
T_{canopy} (^oC)	39.48
T_{ground} (^oC)	49.47
$T_{ambient}$ (^oC)	35.6
$V_{in\ collector}$ (m/s)	0.605
I (W/m^2)	486
ρ (kg/m^3)	1.144
C_p (J/kg.^oC)	1005

Case 3 a: Chimney height = 3.6m

Canopy height = 30cm

Chimney height = 3.6m	
Canopy height = 30cm	
Time= 12noon	
T_{canopy} (^oC)	41.95
T_{ground} (^oC)	46.08
$T_{ambient}$ (^oC)	34
$V_{in\ collector}$ (m/s)	0.775
I (W/m^2)	393.7
ρ (kg/m^3)	1.150
C_p ($J/kg.^oC$)	1005

Chimney height = 3.6m	
Canopy height = 30cm	
Time= 1400	
T_{canopy} (^oC)	45.23
T_{ground} (^oC)	51.28
$T_{ambient}$ (^oC)	35.2
$V_{in\ collector}$ (m/s)	0.333
I (W/m^2)	466.7
ρ (kg/m^3)	1.146
C_p ($J/kg.^oC$)	1005

Chimney height = 3.6m	
Canopy height = 30cm	
Time= 1600	
T_{canopy} (^oC)	41.53
T_{ground} (^oC)	47.18
$T_{ambient}$ (^oC)	37.5
$V_{in\ collector}$ (m/s)	0.433
I (W/m^2)	227.67
ρ (kg/m^3)	1.137
C_p ($J/kg.^oC$)	1005

Case 3 b: Chimney height = 3.6m

Canopy height = 40cm

Chimney height = 3.6m	
Canopy height = 40cm	
Time= 12noon	
T_{canopy} (^oC)	43.5
T_{ground} (^oC)	52.9
$T_{ambient}$ (^oC)	35.1
$V_{in\ collector}$ (m/s)	0.767
I (W/m^2)	459
ρ (kg/m^3)	1.146
C_p ($J/kg.^oC$)	1005

Chimney height = 3.6m	
Canopy height = 40cm	
Time= 1400	
T_{canopy} (^oC)	45.58
T_{ground} (^oC)	53.08
$T_{ambient}$ (^oC)	35
$V_{in\ collector}$ (m/s)	0.742
I (W/m^2)	463
ρ (kg/m^3)	1.147
C_p ($J/kg.^oC$)	1005

Chimney height = 3.6m	
Canopy height = 40cm	
Time= 1600	
T_{canopy} (^oC)	44.43
T_{ground} (^oC)	50.38
$T_{ambient}$ (^oC)	37.3
$V_{in\ collector}$ (m/s)	1.142
I (W/m^2)	342.7
ρ (kg/m^3)	1.138
C_p ($J/kg.^oC$)	1005

Case 3 c: Chimney height = 3.6m

Canopy height = 45cm

Chimney height = 3.6m	
Canopy height = 45cm	
Time= 12noon	
T_{canopy} (^oC)	37.9
T_{ground} (^oC)	45.83
$T_{ambient}$ (^oC)	34.3
$V_{in\ collector}$ (m/s)	0.657
I (W/m^2)	441.3
ρ (kg/m^3)	1.149
C_p ($J/kg.^oC$)	1005

Chimney height = 3.6m	
Canopy height = 45cm	
Time= 1400	
T_{canopy} (^oC)	45.4
T_{ground} (^oC)	52.18
$T_{ambient}$ (^oC)	39.4
$V_{in\ collector}$ (m/s)	0.65
I (W/m^2)	478.7
ρ (kg/m^3)	1.129
C_p ($J/kg.^oC$)	1005

Chimney height = 3.6m	
Canopy height = 45cm	
Time= 1600	
T_{canopy} (^oC)	42.98
T_{ground} (^oC)	48.8
$T_{ambient}$ (^oC)	35
$V_{in\ collector}$ (m/s)	0.75
I (W/m^2)	356.7
ρ (kg/m^3)	1.147
C_p ($J/kg.^oC$)	1005

The calculation is considered convergent if the scaled residual for the continuity equation, the momentum equation, P-1 radiation and the energy equation are less than $1x10^{-6}$. An example of setting up the CFD model in FLUENT is inserted in Appendix A.

3.1.4 Continuity equation:

General:

$$\frac{\partial \rho}{\partial t} + \frac{\partial(\rho v_x)}{\partial x} + \frac{\partial(\rho v_y)}{\partial y} + \frac{\partial(\rho v_z)}{\partial z} = 0$$

For steady state and 2-D flow:

$$\frac{\partial(\rho v_x)}{\partial x} + \frac{\partial(\rho v_y)}{\partial y} = 0$$

3.1.5 Momentum equation:

x-component:

$$\rho\left(v_x \frac{\partial v_x}{\partial x} + v_y \frac{\partial v_x}{\partial y}\right) = -\frac{\partial P}{\partial x} + \mu\left(\frac{\partial^2 v_x}{\partial x^2} + \frac{\partial^2 v_x}{\partial y^2}\right) + \rho g_x$$

y-component:

$$\rho\left(v_x\frac{\partial v_y}{\partial x}+\ v_y\frac{\partial v_y}{\partial y}\right)=-\frac{\partial P}{\partial y}+\mu\left(\frac{\partial^2 v_y}{\partial x^2}+\ \frac{\partial^2 v_y}{\partial y^2}\right)+\rho g_y$$

3.1.6 Energy equation [12]:

$$k\left[\frac{\partial^2 T}{\partial x^2}+\frac{1}{x}\frac{\partial T}{\partial x}+\frac{\partial^2 T}{\partial y^2}\right]+2\mu\left[\frac{2}{3}\left(\frac{\partial v_y}{\partial y}\right)^2+\frac{1}{2}\left(\frac{\partial v_y}{\partial x}\right)^2\right]-C_p\left(pv_y\frac{\partial T}{\partial y}\right)+v_y\frac{\partial P}{\partial y}=0$$

3.1.7 k-epsilon [11]

The standard k-ε model is a semi-empirical model based on model transport equations for the turbulent kinetic energy (k) and its dissipation rate (ε). Flow flows from laminar characteristic to turbulent characteristic. At turbulent, particles hit each other and lose momentum. This causes fluctuations in velocity and due to the fluctuations, Navier-stokes equations are in the form of $\overline{u}+u'$ and $\overline{v}+v'$. The k-ε model is used to compensate for the fluctuating parts which are u' and v'. Thus, kinematic viscosity, τ is:

$$\tau=(\mu+\mu_t)\frac{\partial u}{\partial y}$$

Where μ is dynamic viscosity, μ_t is turbulent viscosity computed by combining k and ε as follows:

$$\mu_t=\rho C_\mu\frac{k^2}{\varepsilon}$$

3.2 Calculations

3.2.1 Solar chimney collector performance

From [6], the product of $\dot{m}$ x ΔT is the main parameter that depicts the performance of the collector. $\dot{m}$ is the air mass flow rate in the system. It can be calculated by using the equation where the system is at steady state;

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

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 ($\dot{m}$) is constant throughout the system.

ΔT is the temperature difference between ambient temperature, $T_{ambient}$ and fluid temperature, T_{fluid}.

$$\Delta T = T_{fluid} - T_{ambient}$$

3.2.2 Collector efficiency

The efficiency of the solar chimney collector can be calculated as shown below [6]:

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

Where;

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

ΔT = collector temperature rise (T_{fluid} - $T_{ambient}$)

R_c = radius of collector

I_o = solar radiation

3.3 Project Planning

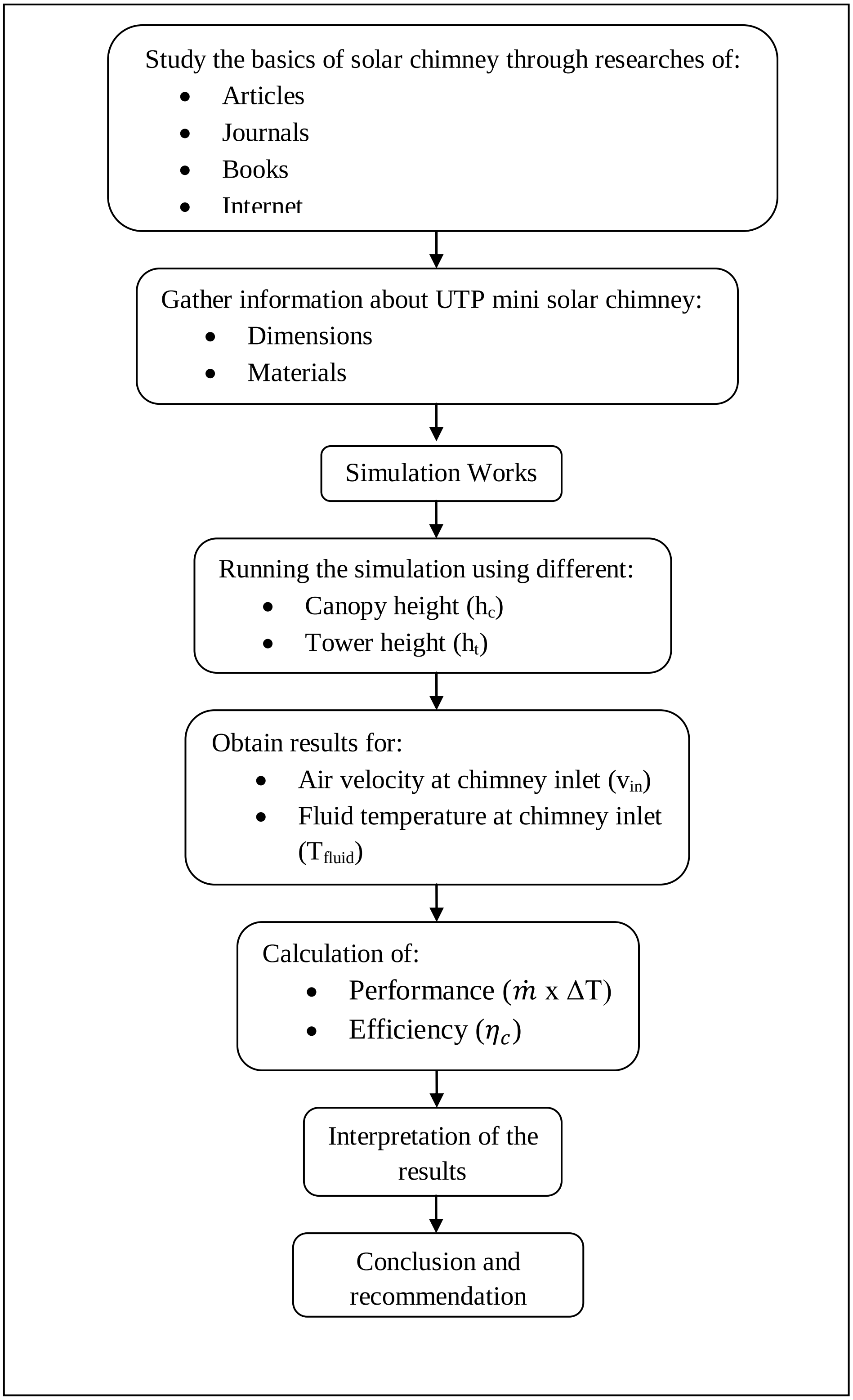


Figure 7: Flow chart of the project

3.3.1 Project Milestone

Table 2: Project milestone for FYP 1

No	Detail	Week														
		1	2	3	4	5	6	7	Mid-Semester Break	8	9	10	11	12	13	14
1	**Selection of Project Topic** **-** Topic selection - Project title proposal submission															
2	**Preliminary Research Work** - Research on Solar Chimney - Research on other related project - Research on other thesis/ journal - Research on software required (FLUENT & GAMBIT) - Doing preliminary report															
3	Submission of Preliminary Report															
4	**Project Work** - Learning about GAMBIT - Building Solar Chimney model using GAMBIT															
5	Submission of Progress Report															
6	Seminar															
7	**Project Work Continues** - Meshing the solar chimney model in GAMBIT -Setup boundary condition of Solar Chimney model															
8	Submission of Interim Report Final Draft															
9	Oral Presentation									**During Study Week**						

Table 3: Project milestone for FYP 2

No	Detail	Week														
		1	2	3	4	5	6	Mid Semester Break	7	8	9	10	11	12	13	14
1	**Project Work Continues** - Simulation work (try and error) - Research on other simulation works															
2	**Submission of Progress Report 1**															
3	**Project Work Continues** - Simulation work															
4	**Submission of Progress Report 2**															
5	**Seminar**															
6	**Project Work Continues** - Simulation works - Obtaining required results - Compare simulation and experimental data															
7	**Poster Exhibition**															
8	**Submission of Dissertation Final Draft**															
9	**Oral Presentation**															*
10	**Submission of Dissertation (hard bound)**															**

* During study week

** 7 days after oral presentation

3.4 Software

1. FLUENT 6.3.26 software
2. Gambit 2.4.6 Software

CHAPTER 4

RESULTS AND DISCUSSIONS

4.1 Validation

In order to validate the simulation model, initial operating conditions were taken from experimental measurements. This is to make comparison between experimental and simulation results and justifies the simulation results obtained.

The following shows information obtained from the experimental work [6]:

Chimney height = 1.6m	
Canopy height = 30cm	
Time= 12noon	
T_{canopy} (^oC)	40.67
T_{ground} (^oC)	48.5
$T_{ambient}$ (^oC)	33.6
$V_{in\ collector}$ (m/s)	0.583
V_{in} (m/s)	0.43
T_{fluid} (^oC)	34.83
ΔT (^oC)	1.23

After inputting the data which are T_{canopy}, T_{ground}, $T_{ambient}$ and $V_{in\ collector}$ into the simulation model, the air velocity at chimney inlet $v_{in,}$ is 2.06 m/s and the fluid temperature T_{fluid} is 34.34^{o}C. The fluid temperature is reasonably in agreement with the experimental value but the air velocity at chimney inlet is different. The difference is due to different value of air density, air viscosity and the assumption made where the ground surface is assumed to be smooth surface.

According to [7], the air velocity should be increasing from the collector inlet to the chimney inlet due to reduction in volume at the tower. Therefore, the result obtained from the simulation is reasonable and hence, the simulation model is validated.

4.2 Calculation of performance and efficiency

A sample calculation for tower height of 1.6m and canopy height of 0.3m (at 12noon):

Performance of the collector = $\dot{m}$ x ΔT

To calculate the mass flow rate, $\dot{m} = \rho_{air}A_c v_{in}$

$= (1.152)(0.01824)(2.06)$

$= 0.04328$

Hence, collector performance = 0.04328 x 0.74

= <u>0.03203</u>

Collector efficiency:

$$\eta_c = \frac{C_p \dot{m} \Delta T}{\pi {R_c}^2 I_o} = \frac{(1005)(0.04328)(2.06)}{\pi(1.05)(402)}$$

$= 0.02313$

4.3 Simulation results

<u>For solar chimney with tower height of 1.6m</u>

Table 4: Simulation results for case study of 1.6m tower height with canopy height of a) 0.3m, b) 0.4m and c) 0.45m

a) Canopy height of 0.3m

Time	A chimney (m^2)	Density (kg/m^3)	V_{in} (m/s)	$T_{ambient}$ (°C)	T_{fluid} (°C)	I (W/m^2)	ΔT (°C)	$\dot{m}\,\Delta T$	η_c
1200	0.01824	1.152	2.06	33.6	34.34	402	0.74	0.03203	0.02313
1400	0.01824	1.144	2.24	35.6	36.48	475	0.88	0.04113	0.02512
1600	0.01824	1.141	1.47	36.4	37.01	273	0.61	0.01866	0.01983

b) Canopy height of 0.4m

Time	A chimney (m^2)	Density (kg/m^3)	V_{in} (m/s)	$T_{ambient}$ (°C)	T_{fluid} (°C)	I (W/m^2)	ΔT (°C)	$\dot{m}\,\Delta T$	η_c
1200	0.01824	1.158	2.47	32.1	33	483	0.9	0.04695	0.02820
1400	0.01824	1.151	2.88	33.9	34.8	498.3	0.9	0.05441	0.03168
1600	0.01824	1.150	2.60	34.1	34.7	262.3	0.6	0.03272	0.03619

c) Canopy height of 0.45m

Time	A chimney (m^2)	Density (kg/m^3)	V_{in} (m/s)	$T_{ambient}$ (°C)	T_{fluid} (°C)	I (W/m^2)	ΔT (°C)	$\dot{m}\,\Delta T$	η_c
1200	0.01824	1.152	1.14	33.7	34.5	441.7	0.8	0.01916	0.01259
1400	0.01824	1.162	4.01	34.0	34.7	331	0.7	0.05949	0.05215
1600	0.01824	1.139	1.85	36.8	37.3	304.3	0.5	0.01922	0.01832

<u>For solar chimney with tower height of 2.6m</u>

Table 5: Simulation for case study of 2.6m tower height with canopy height of a) 0.3m, b) 0.4m and c) 0.45m

a) Canopy height of 0.3m

Time	A chimney (m^2)	Density (kg/m^3)	V_{in} (m/s)	$T_{ambient}$ (^oC)	T_{fluid} (^oC)	I (W/m^2)	ΔT (^oC)	$\dot{m}$ ΔT	η_c
1200	0.01824	1.148	2.12	34.5	35.33	460	0.83	0.03685	0.02324
1400	0.01824	1.142	2.22	36.2	37.06	511.3	0.86	0.03977	0.02256
1600	0.01824	1.143	3.55	35.8	36.4	292.7	0.6	0.04441	0.04402

a) Canopy height of 0.4m

Time	A chimney (m^2)	Density (kg/m^3)	V_{in} (m/s)	$T_{ambient}$ (^oC)	T_{fluid} (^oC)	I (W/m^2)	ΔT (^oC)	$\dot{m}$ ΔT	η_c
1200	0.01824	1.135	3.28	37.9	38.6	558.7	0.7	0.04753	0.02468
1400	0.01824	1.148	5.50	34.6	35.6	492.3	1.0	0.11517	0.06789
1600	0.01824	1.135	5.38	37.9	38.45	407	0.55	0.06126	0.04368

b) Canopy height of 0.45m

Time	A chimney (m^2)	Density (kg/m^3)	V_{in} (m/s)	$T_{ambient}$ (^oC)	T_{fluid} (^oC)	I (W/m^2)	ΔT (^oC)	$\dot{m}$ ΔT	η_c
1200	0.01824	1.154	1.38	33	33.64	424.3	0.64	0.01859	0.01271
1400	0.01824	1.151	5.07	33.8	34.8	522.7	1.0	0.10644	0.05908
1600	0.01824	1.144	3.23	35.6	36.3	486	0.7	0.04719	0.02817

For solar chimney with tower height of 3.6m

Table 6: Simulation results of case study of 3.6m tower height with canopy height of a) 0.3m, b) 0.4m and c) 0.45m

a) Canopy height of 0.3m

Time	A chimney (m^2)	Density (kg/m^3)	V_{in} (m/s)	$T_{ambient}$ (^oC)	T_{fluid} (^oC)	I (W/m^2)	ΔT (^oC)	$\dot{m}$ ΔT	η_c
1200	0.01824	1.150	2.75	34	34.6	393.7	0.6	0.03461	0.02550
1400	0.01824	1.146	1.17	35.6	36	466.7	0.4	0.00978	0.00608
1600	0.01824	1.137	1.52	37.5	38	227.67	0.5	0.01576	0.02008

b) Canopy height of 0.4m

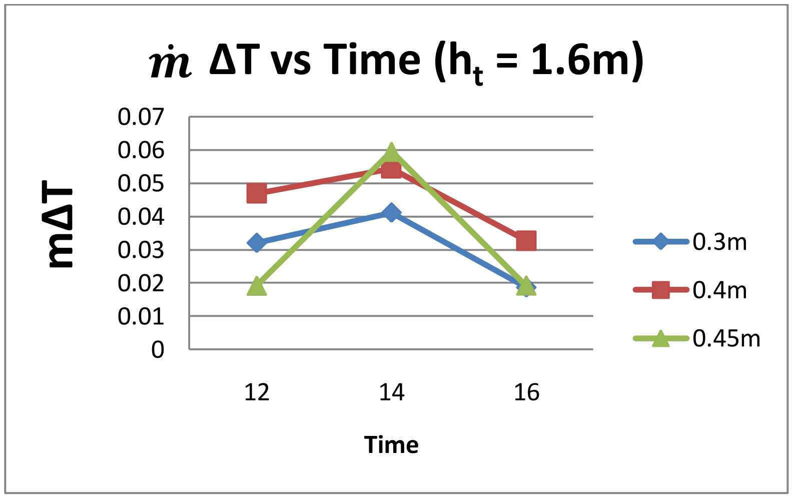
Time	A chimney (m^2)	Density (kg/m^3)	V_{in} (m/s)	$T_{ambient}$ (^oC)	T_{fluid} (^oC)	I (W/m^2)	ΔT (^oC)	$\dot{m}$ ΔT	η_c
1200	0.01824	1.146	3.63	35.1	36	459	0.9	0.06829	0.04317
1400	0.01824	1.147	3.52	35	35.9	463	0.9	0.06628	0.04153
1600	0.01824	1.138	5.41	37.3	38	342.7	0.7	0.07861	0.06655

c) Canopy height of 0.45m

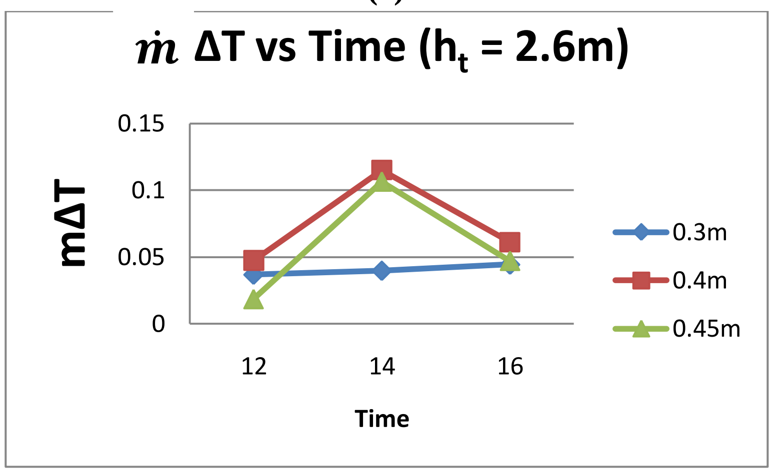
Time	A chimney (m^2)	Density (kg/m^3)	V_{in} (m/s)	$T_{ambient}$ (^oC)	T_{fluid} (^oC)	I (W/m^2)	ΔT (^oC)	$\dot{m}$ ΔT	η_c
1200	0.01824	1.149	3.5	34.3	35.9	441.3	1.6	0.11736	0.07716
1400	0.01824	1.129	3.47	39.4	40.0	478.7	0.60	0.04287	0.02599
1600	0.01824	1.147	4.0	35	35.7	356.7	0.7	0.05858	0.04765

*** Simulation results are shown in colour**

***Others are from experimental work**



(a)



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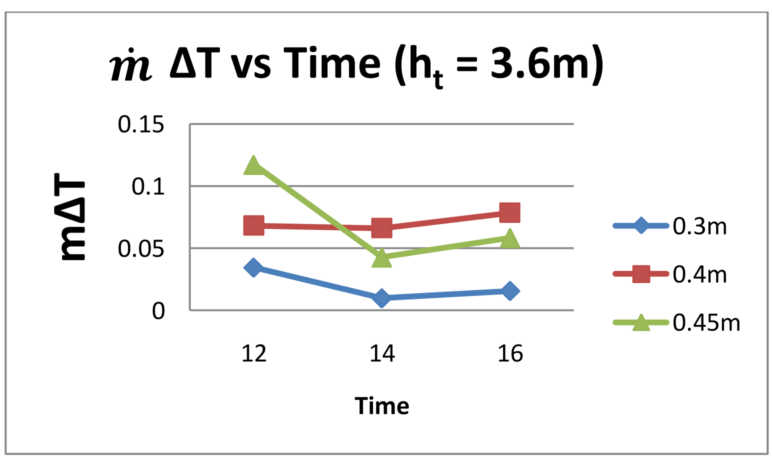
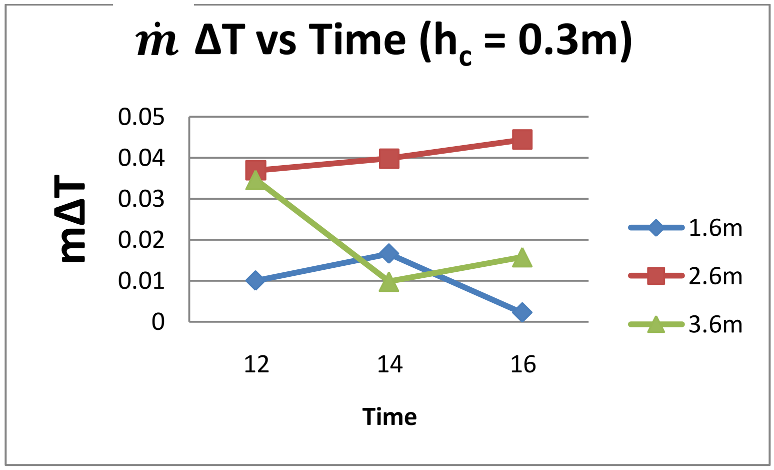


(c)

Figure 8: Simulation data of $\dot{m}\Delta T$ vs Time of variable canopy height at tower height a) 1.6m, b) 2.6m and c) 3.6m



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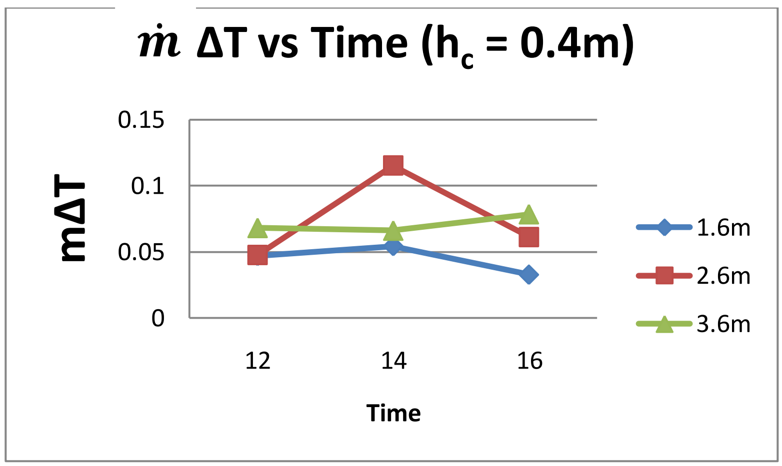

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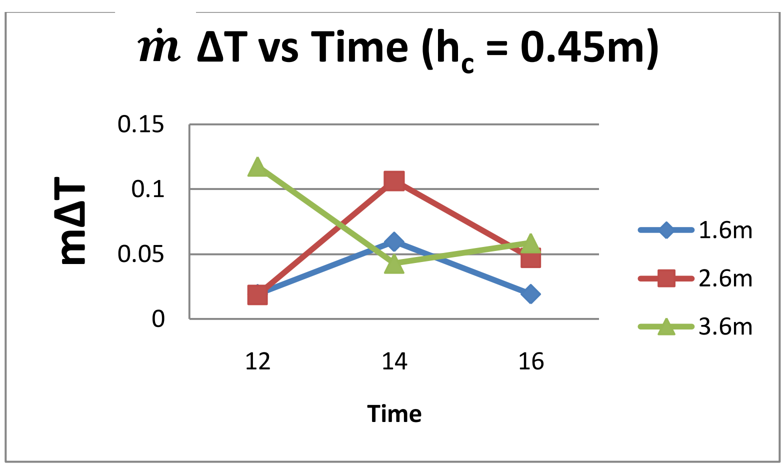
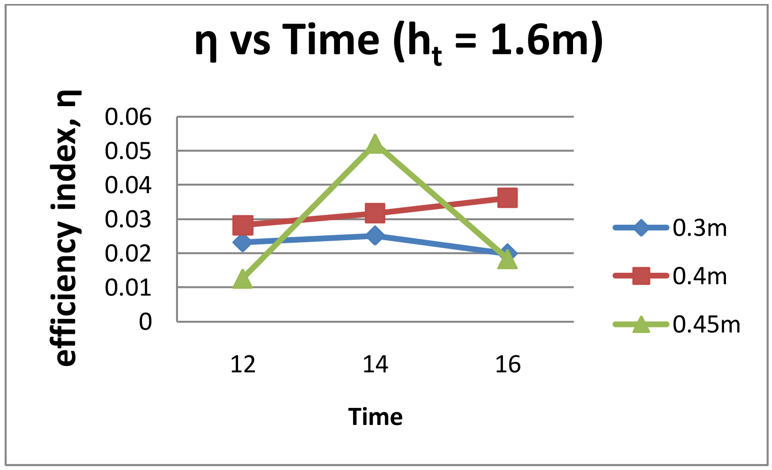
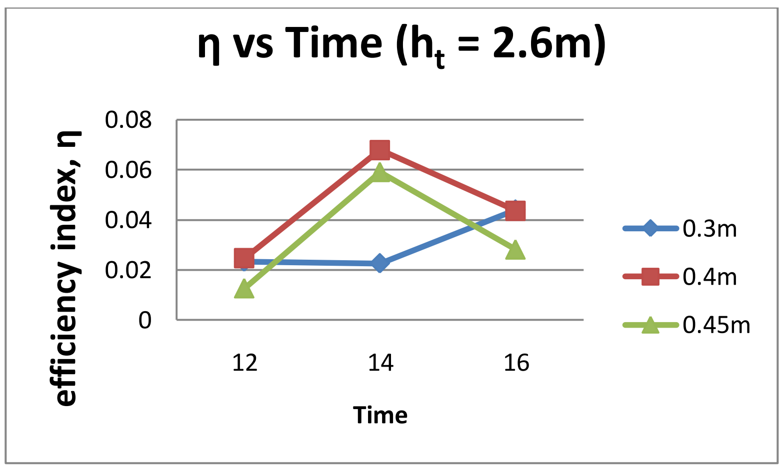


(c)

Figure 9: Simulation data of $\dot{m}\Delta T$ vs Time of variable tower height at canopy height a) 0.3m, b) 0.4m and c) 0.45m



(a)



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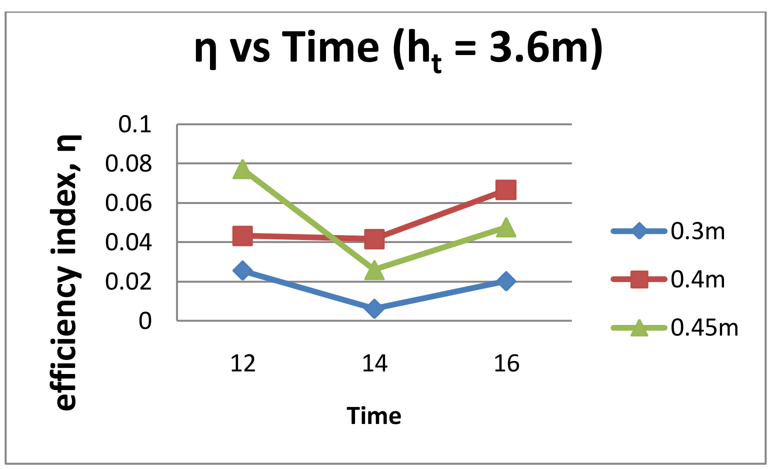
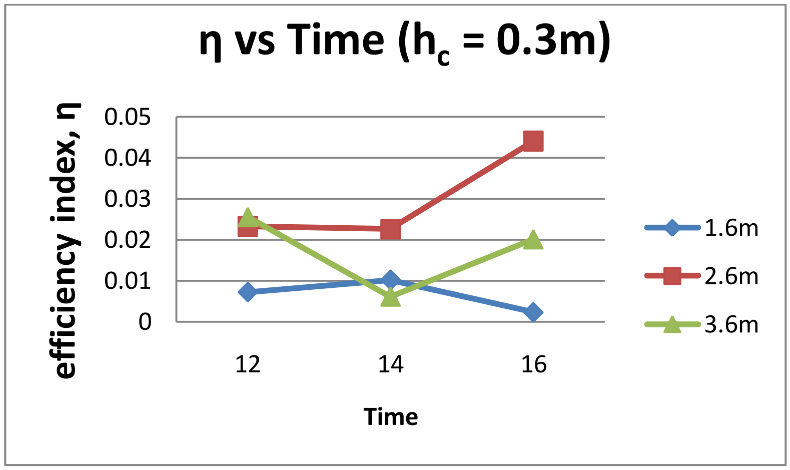
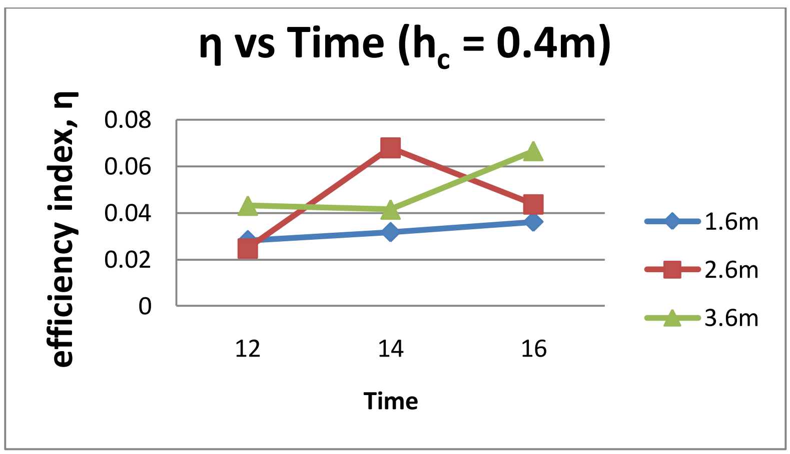


(c)

Figure 10: Simulation data of efficiency index η vs Time of variable canopy height at tower height a) 1.6m, b) 2.6m and c) 3.6m



(a)



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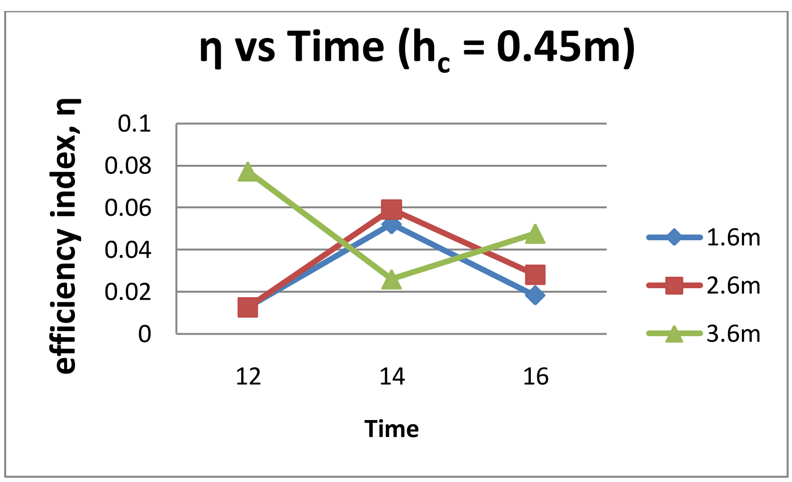


(c)

Figure 11: Simulation data of efficiency index η vs Time of variable tower height at canopy height a) 0.3m, b) 0.4m and c) 0.45m

4.4 Data analysis

The simulation results of the effect of canopy height (h_c) and tower height (h_t) can be referred in Figures 8, 9, 10 and 11. These figures showed that the hourly variation of the performance parameter and its efficiency at 12noon, 2pm and 4pm.

The effects of environmental condition such as ambient temperature ($T_{ambient}$) and collector inlet velocity ($V_{in\ collector}$) has been taken into account to run the simulations and the result such as v_{in} showed some variations.

$\dot{m}\Delta T$ depicts the performance of the collector whereas the efficiency term refers to the whole system [6]. The calculations of the performance and efficiency can be referred in methodology section.

Effect of canopy height

The simulation results of the effect of canopy height (h_c) can be seen shown in figures 8 and 10. Referring to the figures, it is showing that the highest collector performance and system efficiency is when the canopy height (h_c) was set at 0.4m.The results showed that the intermediate canopy height (h_c) is giving the highest collector performance and system efficiency among the studied canopy height (h_c) of 0.3m, 0.4m and 0.45m which is different from the experimental work done by [6] which shows that the highest collector performance and system efficiency is at canopy height 0.3m. Her work is supported by [13], in which her results showed that at lower canopy height, the system performance is better.

Effect of tower height

Referring to figures 9 and 11, the collector performance and system efficiency is better when the tower height is 2.6m. The results showed that the intermediate tower height (h_t) is giving the highest collector performance and system efficiency among the studied tower height (h_t) of 1.6m, 2.6m and 3.6m. The result from the experimental work [6] showed that 3.6m is better due to the difference in pressure along the chimney is larger at higher tower height and thus encourages wind updraft and that leads to the higher efficiency of the system.

Best time for the efficient system

Results show that the solar chimney system is at higher efficiency and performance at 1400 since at that time, the solar intensity is higher compared to other time.

4.5 Discussions

The simulation results are much dependent to the environment condition such as the ambient temperature, solar intensity and wind velocity at certain times which were obtained from experimental work, [6]. The results of the simulations are influenced by the air velocity entering the collector. The wind velocity at certain time is different depending on the weather condition at that area. If the wind velocity is higher when the canopy height (h_c) and tower height (h_t) are set at certain values which showed the lowest collector performance and efficiency, the collector performance and efficiency will be increasing. The ambient temperature also affects the outcome of the results since at certain times, it will be cloudy and the ambient temperature will decrease as also the performance and system efficiency.

The study of the effect of canopy slope angle cannot be preceded since the time for this research is limited. From [12], the results showed that change of the canopy orientation in the solar collector have considerable effects on the performance of the system. The efficiency is increased in the diverging case compared with the parallel case. The best flow characteristic is obtained with converging chimney, where the flow accelerates towards the outlet of the chimney.

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

This research objective is to study the effects of canopy height (h_c), canopy slope angles (Θ) and tower height (h_t) on the performance of a solar chimney. Since the time for this research is limited, the simulation was only performed using different canopy height (h_c) and tower height (h_t).

Based on the validated result, the simulation model is reasonable even though there is difference from the experimental work which is the $V_{in\ collector}$. The result of the validation is consistent with the result from [7] which mentioned that the air velocity should be increasing from the collector inlet to the chimney inlet due to reduction in volume at the tower.

The following can be concluded from the simulation results:

a) The product of $\dot{m}\ x\ \Delta T$ is the main parameter that depicts the performance of the collector.
b) The best system performance of the solar chimney model is when the canopy height (h_c) is 0.4m from the ground.
c) The system shown the best efficiency η at chimney height (h_t) of 2.6m and the canopy height (h_c) is 0.4cm.

5.2 Recommendations

Based on the results obtained from the simulation and the flow of this research, the following are some of the recommendations for developing more and reasonable solar chimney model simulation:

a) Simulate the solar chimney model using the real geometry that has considered the diameter reduction at the chimney tower to achieve more accurate results and measurement of the solar chimney performance.
b) Additional investigation can be done by varying the material for collector and cover.
c) Continue the simulation using different orientations of the canopy slope angles and its effects towards the performance and efficiency of the solar chimney model.

REFERENCES

[1] Schlaich J. The solar chimney: Electricity from the sun. In: Maurer C, editor. Germany: Geislingen;1995.

[2] Haaf W, Friedrich K, Mayr G, Schlaich J. Solar chimneys: Part I: Principle and construction of the pilot plant in Manzanares. International Journal of Solar Energy 1983;2(1):3-20.

[3] Y.J. Dai, H.B. Huang, R.Z. Wang (2002). “Case study of solar chimney power plants in Northwestern regions of China”

[4] Schlaich J, Bergermann R, Schiel W, Weinrebe G (2005). “Design of Commercial Solar Updraft Tower Systems—Utilization of Solar Induced Convective Flows for Power Generation”

[5] HuiLan Huang, Hua Zhang, Yi Huang, Feng Lu (2007). “Simulation Calculation on Solar Chimney Power Plant System”

[6] Toh Jia Lin (2010). “Design, Fabrication And Test of Variable Height Solar Chimney”, *Hons Thesis*, Universiti Teknologi PETRONAS, Malaysia.

[7] Sh. Khoshmanesh (2006). “Computer Simulation of Solar Updraft Tower Systems to Describe the Variation of Velocity with Essential Parameters of the Systems”

[8] J.A Jones, Convection heat transfer, 2nd edition, Wiley and Sons Inc, New York, 1995

[9] H.K.Versteeg and W Malalasekera, An introduction to computational fluid dynamics the finite volume method, Addison Wesley Longman Limited, 1995

[10] FLUENT Inc.,FLUENT 6.3 Tutorial Guide, Fluent Inc. 2006

[11] Khor Yin Yin (2009). “Numerical Simulation of Solar-Flue Gas Chimney for Energy Recovery”, *Hons Thesis*, Universiti Teknologi PETRONAS, Malaysia.

[12] H.H. Al-Kayiem, Q. A. Al-Nakeeb (2006). “Geometry Alteration Effect on the Performance of a Solar-Wind Power System”

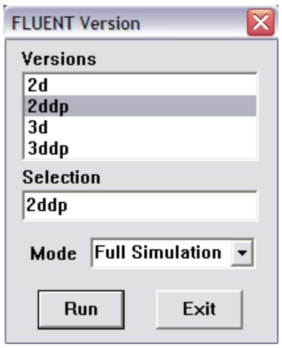
[13] Shyia (2002), “Parametric Study of Solar Chimney Performance”, *MSc* Thesis, Saddam University, Baghdad.

APPENDIX A: Setting up CFD model in FLUENT

1. Launch FLUENT

Lab Apps > FLUENT 6.3.26

Select “2ddp” (2D double-precision) and click Run



2. Import File

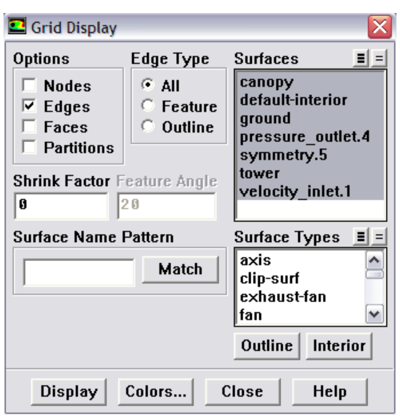
Main Menu > File > Read > Case...

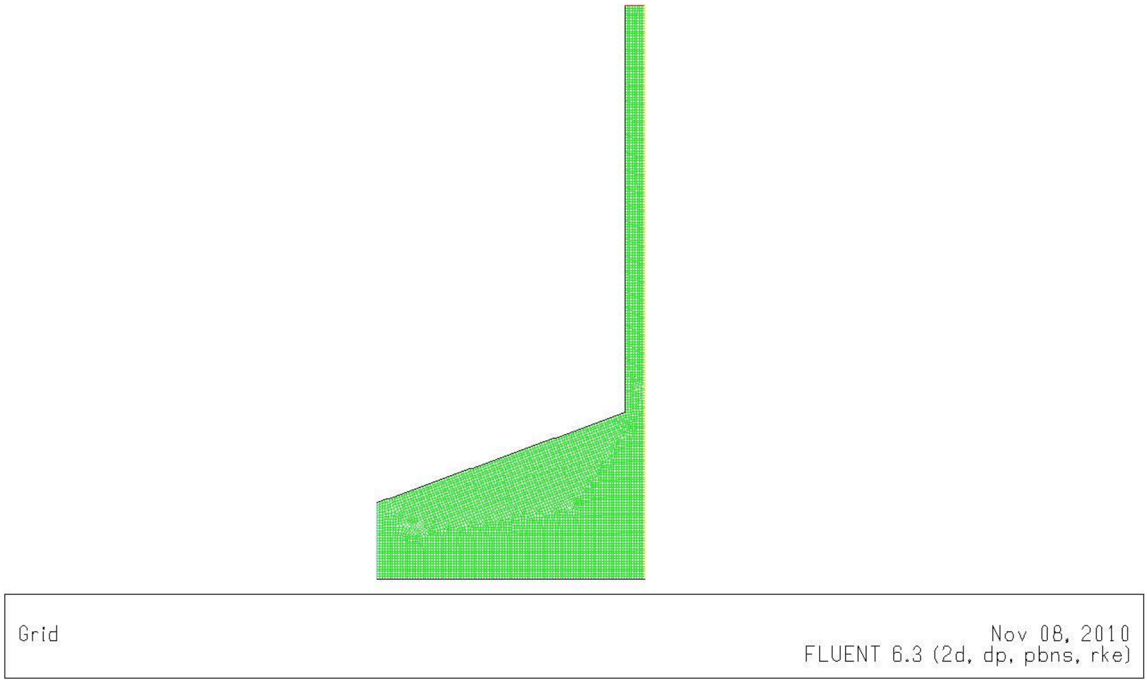
3. Analyze Grid

Grid > Check

(FLUENT perform various checks on the mesh and reports the progress in the console window. Pay particular attention to the minimum volume. Make sure this is a positive number)

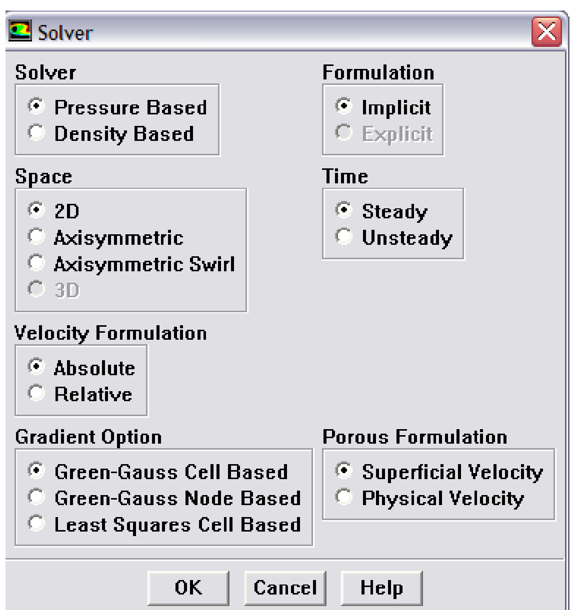
Display > Grid...





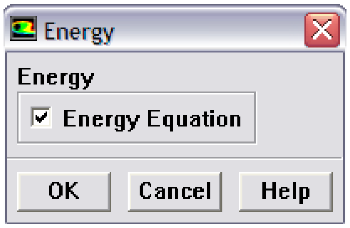
4. Define Properties

Define > Models > Solver

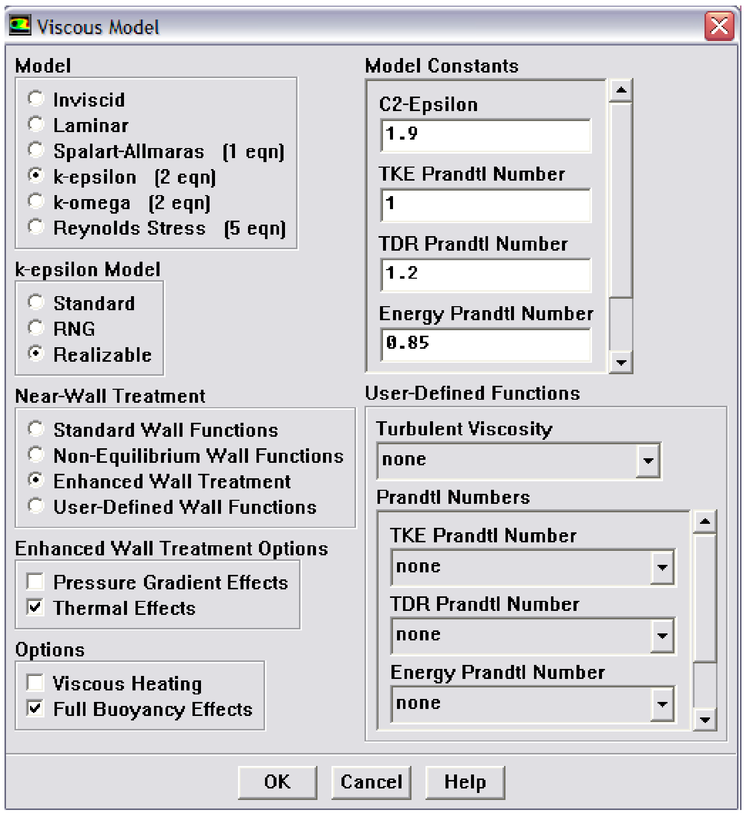


Keep the default solver settings.

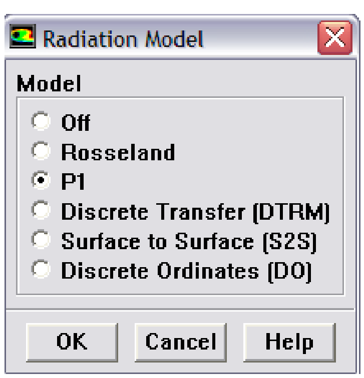
Define > Models > Energy



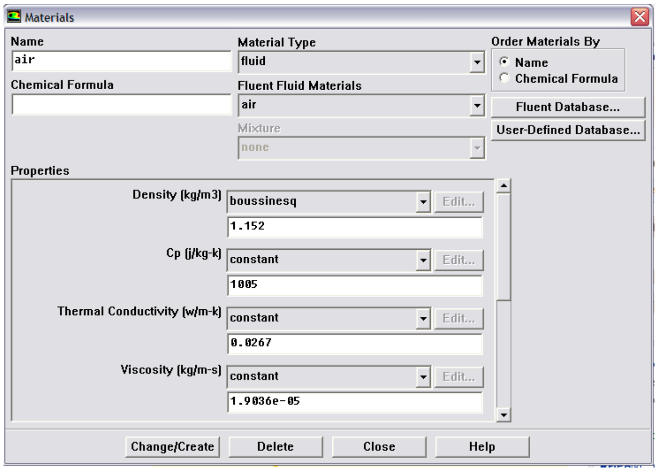
Define > Models > Viscous

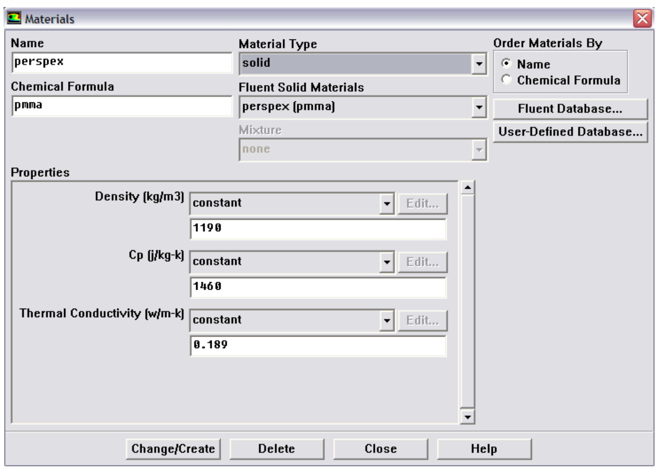


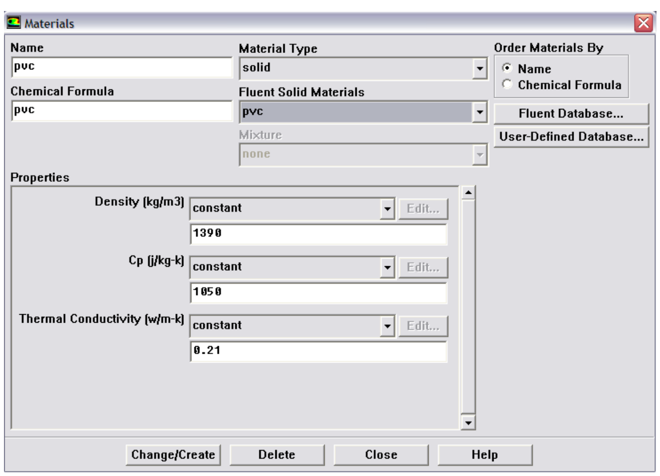
Define > Models > Radiation

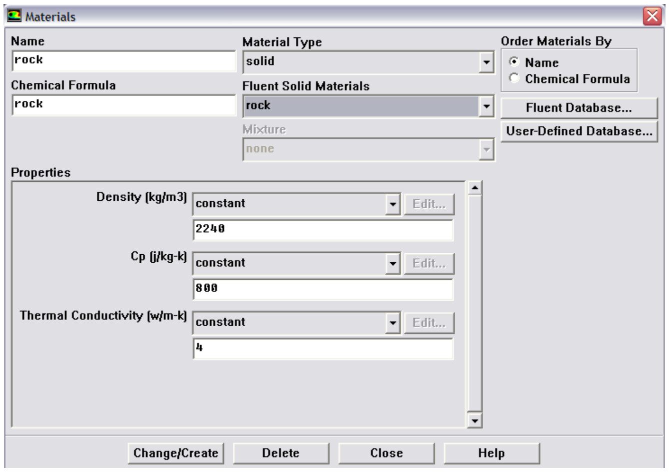


Define > Materials

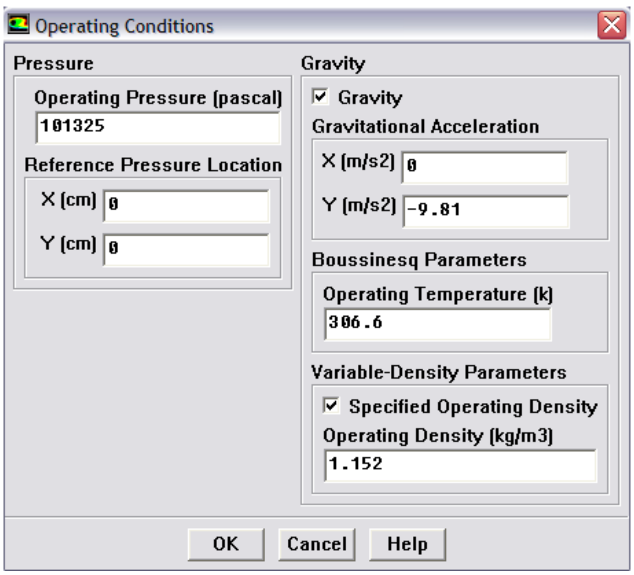




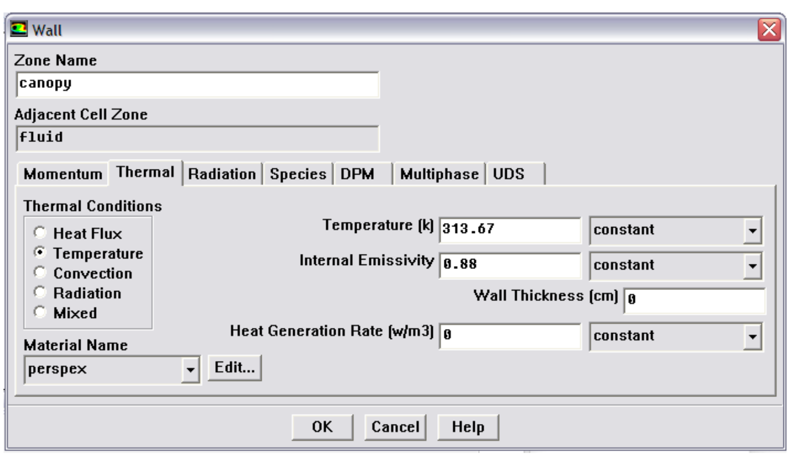


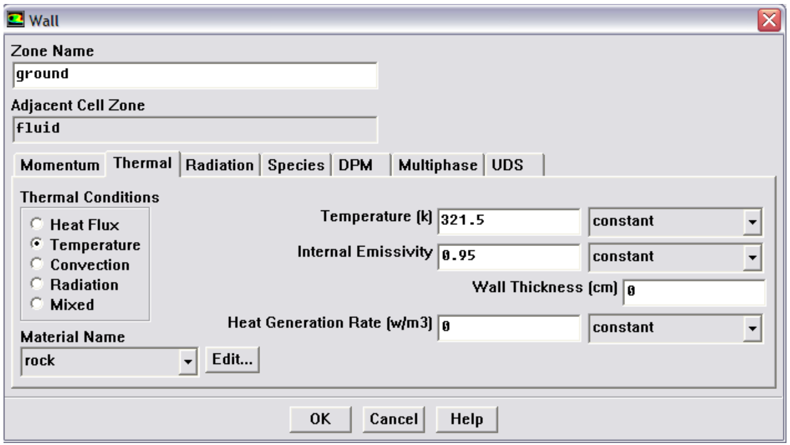


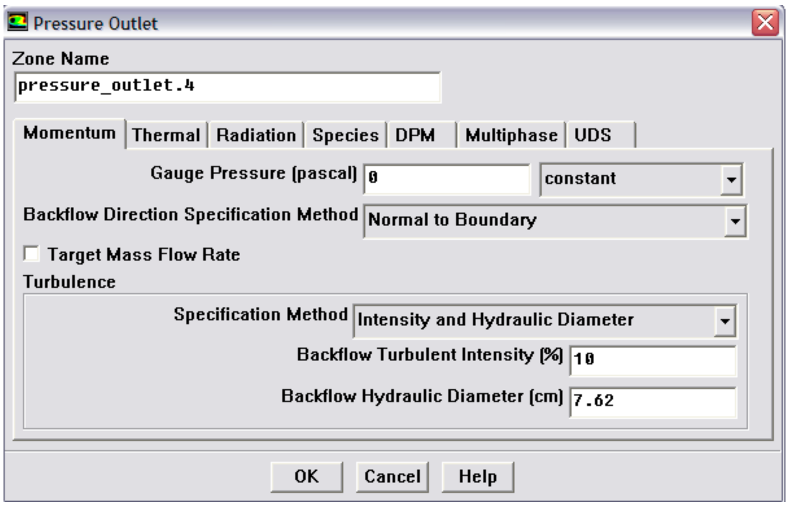
Define > Operating Conditions

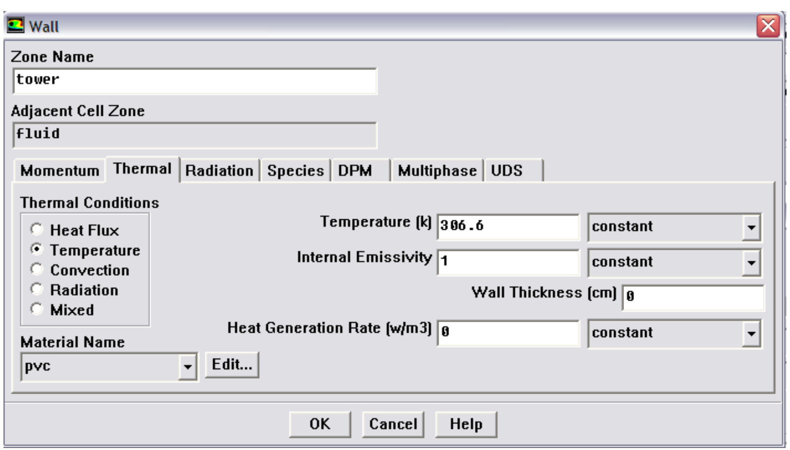


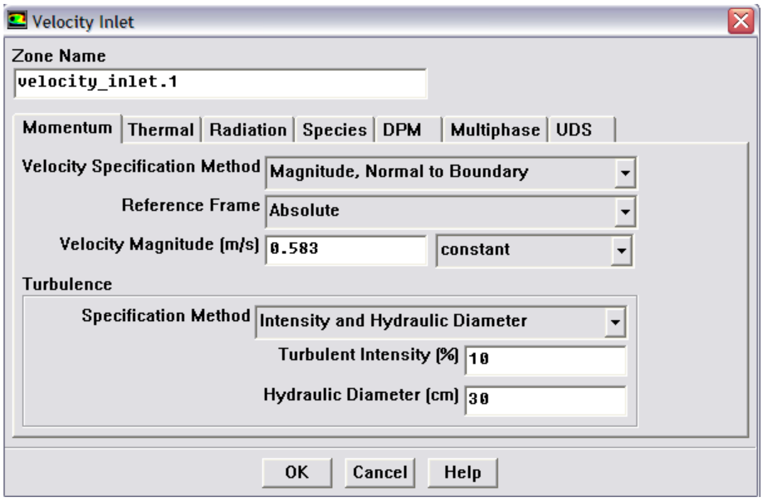
Define > Boundary Conditions



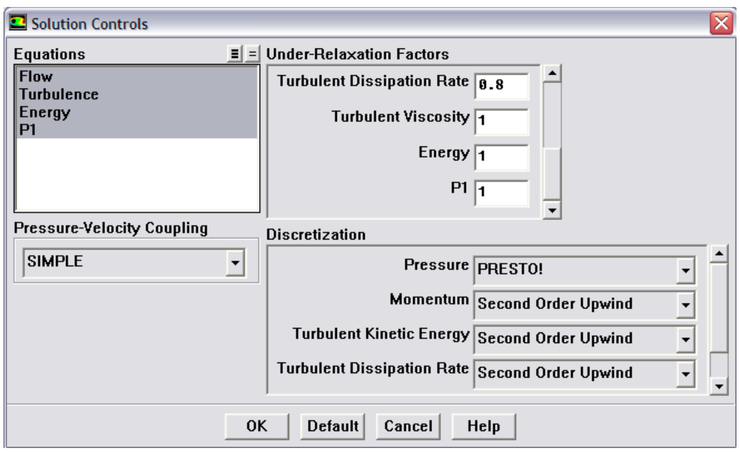

Wall
Zone Name
ground
Adjacent Cell Zone
fluid
Momentum
Thermal
Radiation
Species
DPM
Multiphase
UDS
Thermal Conditions
Heat Flux
Temperature
Convection
Radiation
Mixed
Temperature (k)
321.5
constant
Internal Emissivity
0.95
constant
Wall Thickness (cm)
0
Heat Generation Rate (w/m3)
0
constant
Material Name
rock
Edit...
OK
Cancel
Help


Pressure Outlet
Zone Name
pressure_outlet.4
Momentum
Thermal
Radiation
Species
DPM
Multiphase
UDS
Gauge Pressure (pascal)
0
constant
Backflow Direction Specification Method
Normal to Boundary
Target Mass Flow Rate
Turbulence
Specification Method
Intensity and Hydraulic Diameter
Backflow Turbulent Intensity (%)
10
Backflow Hydraulic Diameter (cm)
7.62
OK
Cancel
Help

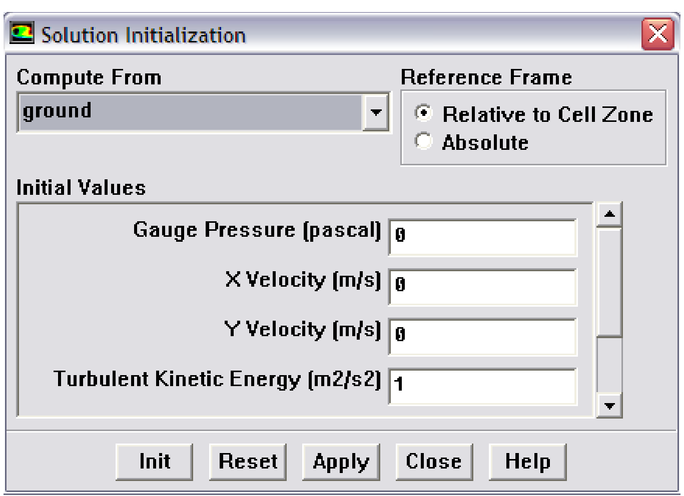

Wall
Zone Name
tower
Adjacent Cell Zone
fluid
Momentum
Thermal
Radiation
Species
DPM
Multiphase
UDS
Thermal Conditions
Heat Flux
Temperature
Convection
Radiation
Mixed
Temperature (k)
306.6
constant
Internal Emissivity
1
constant
Wall Thickness (cm)
0
Heat Generation Rate (w/m3)
0
constant
Material Name
pvc
Edit...
OK
Cancel
Help



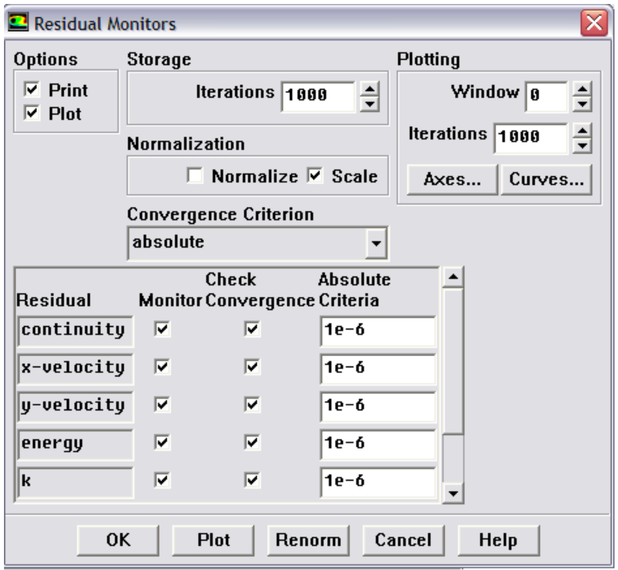
Solve > Control > Solution



Solve > Initialize > Initialize...

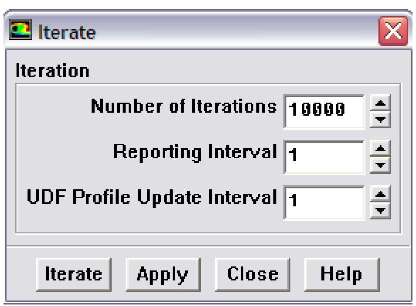


Plot > Residuals...



Main Menu > File > Write > Case File...

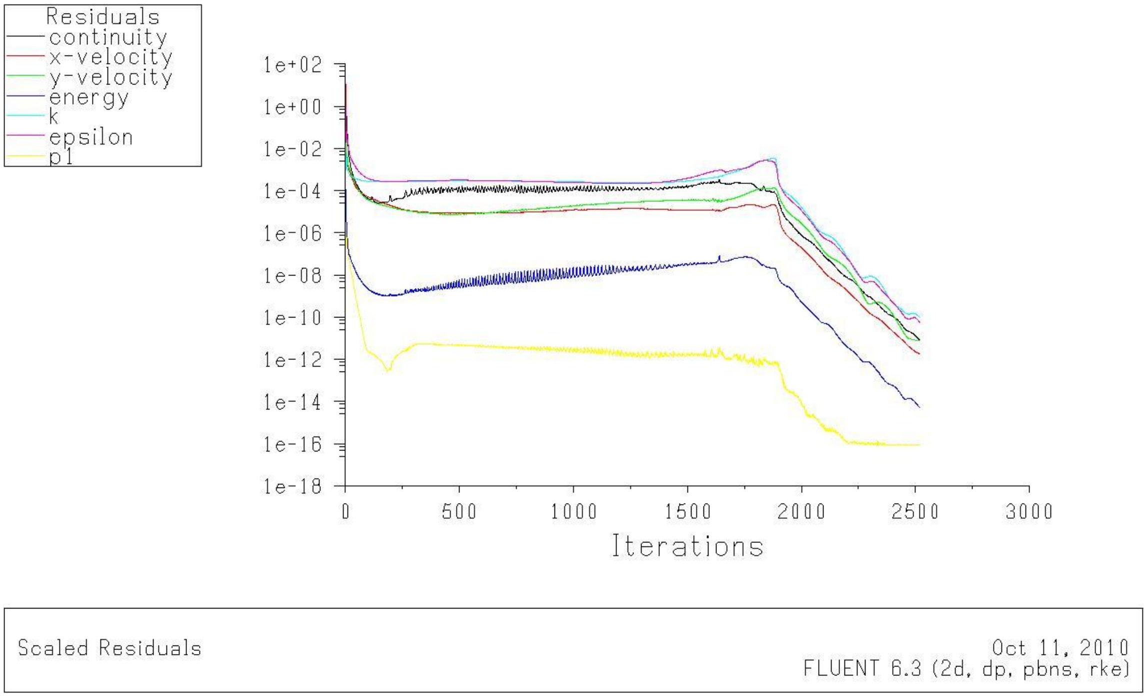
Solve > Iterate



Main Menu > File Write > Data

(Save the solution after the solution is converged)

APPENDIX B: Sample of residual plot for canopy height of 0.3m and tower height of 1.6m at 12noon.



APPENDIX C: Properties of air at certain ambient temperature ($T_{ambient}$)

$T_{ambient}$ (°C) = 33.6	
ρ (kg/m^3)	1.152
C_p (J/kg.°C)	1005
Thermal conductivity(W-m°C)	0.02665
Thermal expansion coefficient (1/°C)	3.2736×10^{-3}
Viscosity (kg/m.s)	1.9036×10^{-5}

$T_{ambient}$ (°C) = 35.6	
ρ (kg/m^3)	1.144
C_p (J/kg.°C)	1005
Thermal conductivity(W-m°C)	0.02679
Thermal expansion coefficient (1/°C)	3.2506×10^{-3}
Viscosity (kg/m.s)	1.9133×10^{-5}

$T_{ambient}$ (°C) = 36.4	
ρ (kg/m^3)	1.141
C_p (J/kg.°C)	1005
Thermal conductivity(W-m°C)	0.02685
Thermal expansion coefficient (1/°C)	3.2414×10^{-3}
Viscosity (kg/m.s)	1.9171×10^{-5}

$T_{ambient}$ (°C) = 32.1	
ρ (kg/m^3)	1.158
C_p (J/kg.°C)	1005
Thermal conductivity(W-m°C)	0.02655
Thermal expansion coefficient (1/°C)	3.2909×10^{-3}
Viscosity (kg/m.s)	1.8963×10^{-5}

$T_{ambient}$ (°C) = 33.9	
ρ (kg/m^3)	1.151
C_p (J/kg.°C)	1005
Thermal conductivity(W-m°C)	0.02667
Thermal expansion coefficient (1/°C)	3.2702×10^{-3}
Viscosity (kg/m.s)	1.9050×10^{-5}

$T_{ambient}$ (°C) = 34.1	
ρ (kg/m^3)	1.150
C_p (J/kg.°C)	1005
Thermal conductivity(W-m°C)	0.02669
Thermal expansion coefficient (1/°C)	3.2679×10^{-3}
Viscosity (kg/m.s)	1.9060×10^{-5}

$T_{ambient}$ (°C) = 33.7	
ρ (kg/m^3)	1.152
C_p (J/kg.°C)	1005
Thermal conductivity(W-m°C)	0.02666
Thermal expansion coefficient (1/°C)	3.2725x10^{-3}
Viscosity (kg/m.s)	1.9041x10^{-5}

$T_{ambient}$ (°C) = 34.0	
ρ (kg/m^3)	1.150
C_p (J/kg.°C)	1005
Thermal conductivity(W-m°C)	0.02668
Thermal expansion coefficient (1/°C)	3.2690x10^{-3}
Viscosity (kg/m.s)	1.9055x10^{-5}

$T_{ambient}$ (°C) = 36.8	
ρ (kg/m^3)	1.139
C_p (J/kg.°C)	1005
Thermal conductivity(W-m°C)	0.02688
Thermal expansion coefficient (1/°C)	3.2368x10^{-3}
Viscosity (kg/m.s)	1.9191x10^{-5}

$T_{ambient}$ (°C) = 34.5	
ρ (kg/m^3)	1.148
C_p (J/kg.°C)	1005
Thermal conductivity(W-m°C)	0.02672
Thermal expansion coefficient (1/°C)	3.2633x10^{-3}
Viscosity (kg/m.s)	1.9079x10^{-5}

$T_{ambient}$ (°C) = 36.2	
ρ (kg/m^3)	1.142
C_p (J/kg.°C)	1005
Thermal conductivity(W-m°C)	0.02683
Thermal expansion coefficient (1/°C)	3.2437x10^{-3}
Viscosity (kg/m.s)	1.9162x10^{-5}

$T_{ambient}$ (°C) = 35.8	
ρ (kg/m^3)	1.143
C_p (J/kg.°C)	1005
Thermal conductivity(W-m°C)	0.02681
Thermal expansion coefficient (1/°C)	3.2483x10^{-3}
Viscosity (kg/m.s)	1.9142x10^{-5}

$T_{ambient}$ (°C) = 37.9	
ρ (kg/m^3)	1.135
C_p (J/kg.°C)	1005
Thermal conductivity(W-m°C)	0.02695
Thermal expansion coefficient (1/°C)	3.2242×10^{-3}
Viscosity (kg/m.s)	1.9244×10^{-5}

$T_{ambient}$ (°C) = 34.6	
ρ (kg/m^3)	1.148
C_p (J/kg.°C)	1005
Thermal conductivity(W-m°C)	0.02672
Thermal expansion coefficient (1/°C)	3.2621×10^{-3}
Viscosity (kg/m.s)	1.9084×10^{-5}

$T_{ambient}$ (°C) = 33.0	
ρ (kg/m^3)	1.154
C_p (J/kg.°C)	1005
Thermal conductivity(W-m°C)	0.02661
Thermal expansion coefficient (1/°C)	3.2805×10^{-3}
Viscosity (kg/m.s)	1.9007×10^{-5}

$T_{ambient}$ (°C) = 33.8	
ρ (kg/m^3)	1.151
C_p (J/kg.°C)	1005
Thermal conductivity(W-m°C)	0.02667
Thermal expansion coefficient (1/°C)	3.2713×10^{-3}
Viscosity (kg/m.s)	1.9046×10^{-5}

$T_{ambient}$ (°C) = 35.6	
ρ (kg/m^3)	1.144
C_p (J/kg.°C)	1005
Thermal conductivity(W-m°C)	0.02679
Thermal expansion coefficient (1/°C)	3.2506×10^{-3}
Viscosity (kg/m.s)	1.9133×10^{-5}

$T_{ambient}$ (°C) = 34.3	
ρ (kg/m^3)	1.149
C_p (J/kg.°C)	1005
Thermal conductivity(W-m°C)	0.02670
Thermal expansion coefficient (1/°C)	3.2656×10^{-3}
Viscosity (kg/m.s)	1.9070×10^{-5}

$T_{ambient}$ (°C) = 39.4	
ρ (kg/m^3)	1.129
C_p (J/kg.°C)	1005
Thermal conductivity(W-m°C)	0.02706
Thermal expansion coefficient (1/°C)	3.2069×10^{-3}
Viscosity (kg/m.s)	1.9316×10^{-5}

$T_{ambient}$ (°C) = 35.0	
ρ (kg/m^3)	1.147
C_p (J/kg.°C)	1005
Thermal conductivity(W-m°C)	0.02675
Thermal expansion coefficient (1/°C)	3.2575×10^{-3}
Viscosity (kg/m.s)	1.9104×10^{-5}