Analytical and CFD Simulation of an on-roof Wind Generator Using Biomass

by

Thembinkosi Robert Khumalo

Dissertation submitted in partial fulfilment of

the requirements for the

Bachelor of Engineering (Hons)

(Mechanical Engineering)

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CERTIFICATION OF APPROVAL

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A project dissertation submitted to the
Mechanical Engineering Programme
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BACHELOR OF ENGINEERING (Hons)
(MECHANICAL ENGINEERING)

Approved by,

____
(Name of Main Supervisor)

UNIVERSITI TEKNOLOGI PETRONAS

TRONOH, PERAK

JANUARY 2008

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.

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THEMBINKOSI ROBERT KHUMALO

ABSTRACT

Solar systems usually suffers the non-continuous availability of solar insolation e.g. during the night and in cloudy days. The integration of biomass with solar systems may represent a good solution for the application which is under consideration in the "on-roof solar chimney". This report highlights the importance of understanding the combustion process for efficient burning of the biomass waste and also point out one of the reasons why biomass waste is not fully utilized. Mathematical modelling of the system is the main focus of this report.

Preliminary design of the system for two cases is provided. On Case I the fluid stream to the Savonius rotor is the flue gases only. As the flue gases flow through the roof heat is lost to the ambient air through the glass the glass canopy. The lost heat can be utilized by putting an absorber layer between the insulated roof and the glass canopy and allowing the ambient air to pass between the absorber and the canopy. This provides the basis for Case II which is to make use of the heat loss through the canopy. The resulting air stream is mixed with the flue gas stream before entering the on-roof chimney, and the resulting stream is directed to the rotor on the roof to generate power.

From the simulations it is shown that a significant amount of the heat carried by the flue gases leaves through the on-roof chimney and only 10% is lost through the canopy for Case I and Case II reduces the heat lost through the canopy by 3% and the output power is increased by 74% per unit width of the house. The analysis of the system proves that there is potential in biomass being used to generate electricity for domestic applications with further modifications to the roof dimensions and the configuration of the Savonius wind rotor.

ACKNOWLEDGEMENT

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Nomenclatures

T	temperature (^{0}C)
U	overall heat transfer coefficient (W/m^2 ^{0}C)
$\dot{Q}$	heat transferred (Watts)
$\dot{m}$	mass flow rate (kg/s)
V	velocity (m/s)
$h_{2,3}$	enthalpy at point 2 and 3
A	area (m^2)
c_p	specific heat constant (J/kg. K)
Q	volumetric flow rate (m^3/s)
M	molecular mass (kg/kmol)
k	thermal conductivity (W/m.K)
Nu	Nusselt number
Pr	Prandlt number
Cp	power coefficient

Greek symbols

ρ	density (kg/m^3)
μ	dynamic viscosity (kg/m.s)

α	species number

Subscripts

a	ambient temperature
a, b	inlet a or b
ab	absorber
g	glass
1, 2, 3 and 4	points on the drawings
fg	flue gases
i, ch	intermediate chimney
c	canopy

CHAPTER 1

INTRODUCTION

1.1 Background

The energy demand is increasing all over the world which leads to an increase in the greenhouse gases, and on the other hand the energy sources such as fossil fuels are getting depleted. There is a need to utilize the renewable and environmentally friendly energy sources such as solar, wind, biomass, etc. Research has shown that biomass can provide an environmentally friendly and sustainable energy for domestic and industrial applications.

1.2 Problem Statement

Solar energy can be exploited amongst other ways by converting the house unit roof into a collector covered with a glass canopy. The absorbed solar radiations will be converted to thermal energy in the collector and then transferred to the adjacent air particles by convection heat transfer. This will cause activation of the air particles and will generate air flow stream, which will be directed to the wind turbine on the roof top.

This applies during sunny days, what happens when the solar radiation is at its minimum and at night? Biomass can also be exploited by doing some modifications to the "on-roof solar chimney" system to use both the solar radiation and biomass as energy sources. The activated air particles resulting from biomass system and from integration system can be guided to operate a wind rotor to produce power.

1.3 Objectives

The objectives of the project are;

- To carry out a research to find property data for three types of biomass.
- To perform an analytical performance analysis of the on-roof wind generator system by biomass.
- To use the available CFD software to simulate and evaluate the performance of the system.

1.4 Scope of study

The project will cover the research on the biomass properties and on the combustion products for the three selected types of solid biomass waste which will be selected later in terms of availability. Normal Malaysian house will be selected for the dimension of the model which will further aid in designing the on-roof wind generator. The system analysis will be carried out in two ways; the first part will cover the mathematical modelling of the system and the second part will envelop the CFD simulation of the system using the available software's in the Mechanical engineering department. The last part will be to compare the two results from the simulation and the analytical modelling and draw conclusions and make necessary recommendations.

1.5 Significance of the work

The project has a great significance when it comes to making use of the available renewable energy sources and in remote areas it plays an important role in making sure that there is a continuous flow of energy. The integration of the sustainable energy sources is of great importance in making sure that the energy systems are economical thus helping the private and public sector to diversify their energy sources.

CHAPTER 2

LITETATURE REVIEW

Solar energy is the energy from the sun and is considered the mother of most of the renewable energies like wind, water, etc. The solar insolation reaching the surface of the earth depends on;

- Obliquity – which is the angle between the surface and the beam of insolation
- The length of the air mass through which the beam has to pass

Both of the factors according to Shepherd and Shepherd depends of the altitude of the sun above the earth hence in tropical areas they receive more solar radiation than on the poles due to the distance of the sun to the earth.

This energy from the sun can be utilized in many ways, it can be used directly for heating water and air, can be converted directly to electricity using photovoltaic cells, to electricity using a solar chimney, etc. In hot-arid climates there is a need for cooling which consumes a lot of energy for example in Al-Ain City, UAE as pointed out by AboulNaga and Abdrabboh a two-story residential building uses 186 $kW/h/m^2$. AboulNaga and Abdrabboh used a combine wall-roof chimney to improve the night ventilation; the observed that the air flow rate depends on the height of the roof and it showed promising results towards reducing the cooling load in the area.

Bernardes, Vob and Weinrebe define a solar chimney as a power generating facility, which uses solar energy to heat the air flowing inside the chimney and converts the solar energy to internal energy of the air and thus to kinetic energy which is converted to electricity using a suitable wind turbine. They observed that the power output can be increased by increasing the chimney height, collector area and the transmittance of the collector.

Biomass is a type of waste which includes tree and shrubs, agricultural, all forms of human, animal and plant waste, etc that can be converted into energy. Biomass can be converted in useful forms of energy by combustion, dry chemical process and aqueous process. Direct combustion produces lots of energy compared to the other conversion method since those minimum losses due to the energy conversion process. It is worth pointing out that the CO2 emissions from biomass when compared to the emissions of electrical power plants using coal or oil and gas, the biomass power plant produces very little emissions of about 16g of CO_2 per kWh, which makes it an environmental friendly renewable energy source.

About 12% of the primary energy supply in the world is accounted to biomass and in developing countries biomass accounts for 40% to 50% of the primary energy. Biomass wastes are not fully utilized because of amongst other reasons, the lack of information regarding the fuel feeding as well as the combustion and emission characteristics of biomass wastes [7].

The combustion process needs to be understood perfectly when designing a combustion system in order to achieve high combustion efficiency. Solid biomasses waste under goes the following events; heating up, drying, devolatilization and lastly the combustion of volatiles and char [7]. The influence of temperature, drying, the composition of volatile matter, are very important in understanding the combustion process, figure 1 shows the description of the combustion process of straw or wood.

Figure 1 shows the burning process of the biomass wastes, it is observed that temperature of the flue gases increases as the mass fraction increases.

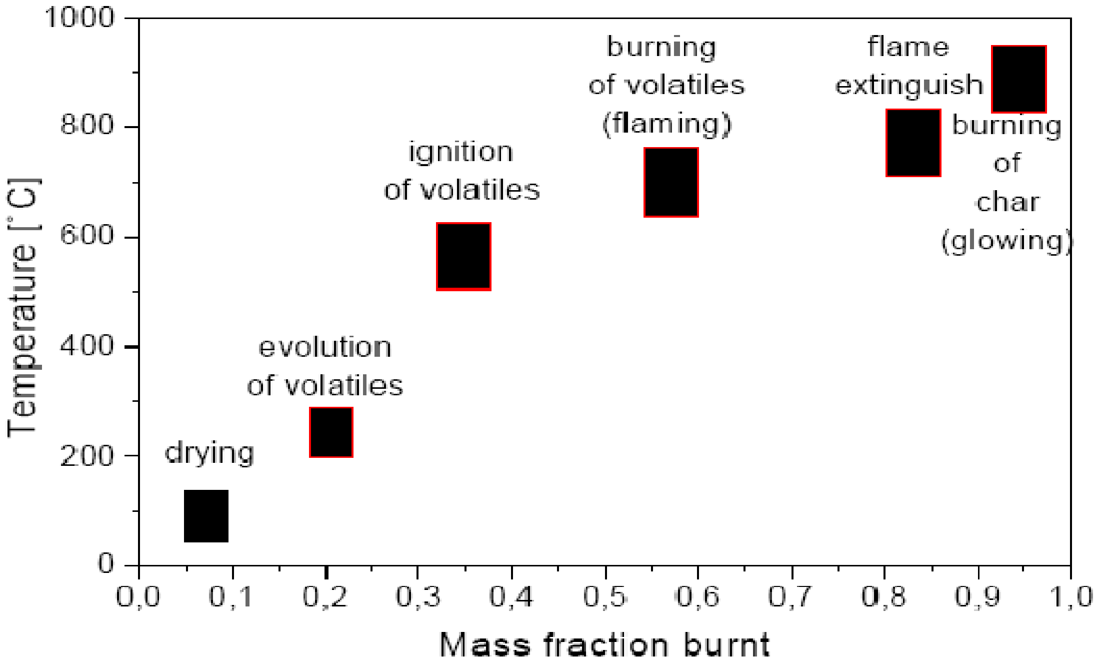


Figure 1: Schematic description of the combustion process of a lump of straw or wood.

Madhlopa and Ggwalo constructed a solar dryer with thermal storage and biomass backup heater; the heater consisted of a grill to burn the biomass, a baffle to direct the flow inside the drum, etc as shown in the figure 2. It was observed that closing the burner door reduces the rate of combustion and opening it leads to higher plenum temperatures. It was also observed that to get higher flow rates the burner door has be adjusted to allow continuous flow of air and increase the combustion rate while controlling the amount of excess air.

This project aims at integrating the biomass system into the on-roof solar chimney for domestic purposes to make use of the energy in the flue gases by directing it to the Savonius rotor on the roof. Basic heat transfer equations for convection and conduction together with the energy and continuity equations are used to describe the system mathematically.

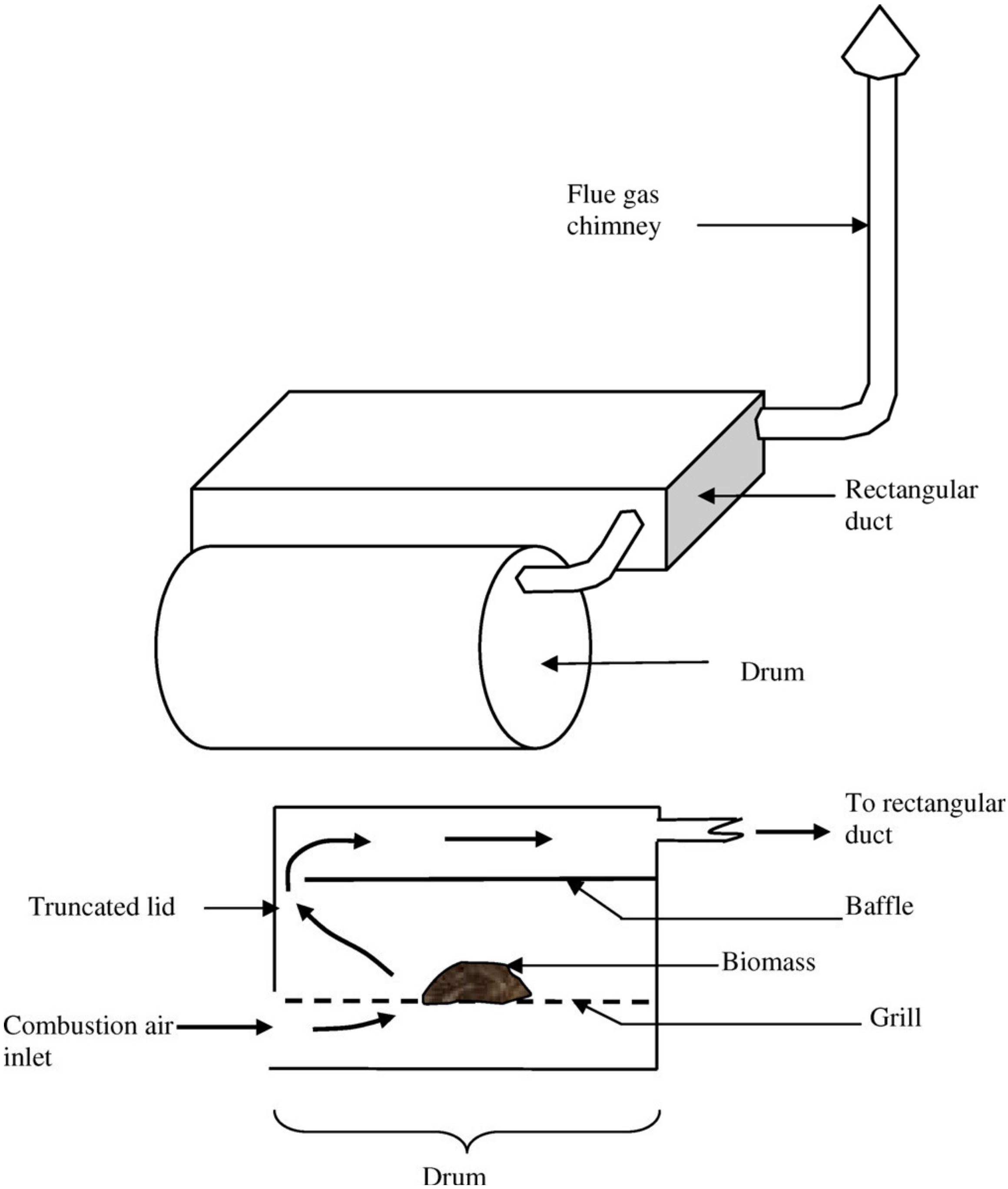


Figure 2: Biomass burner for solar dryer with backup heater.

CHAPTER 3

METHODOLOGY

3.1 Method of research

The research project will be carried out in the following approach;

- Research on properties and combustion products properties for three types of solid biomass fuels.
- Analytical modelling of the hydrothermal mechanism governing the system
- CFD simulation of the system using FLUENT and GAMBIT
- Gantt chant of the project as stipulated by ME department (next page)
- Work flow chart (next page after the Gantt chart)

3.2 Gantt Chat

Suggested Milestone for the First Semester of 2-Semester Final Year Project

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	■	■													
2	Preliminary Research Work		■	■	■											
3	Submission of Preliminary Report				●											
4	Seminar 1 (optional)					■	■	■								
5	Project Work					■	■	■								
6	Submission of Progress Report									●						
7	Seminar 2 (compulsory)										■	■	■	■		
8	Project work continues									■	■	■	■	■		
9	Submission of Interim Report Final														●	
10	Oral Presentation															●

● Suggested milestone

■ Process

Suggested Milestone for the Second Semester of 2-Semester Final Year Project

No.	Detail/ Week	1	2	3	4	5	6	7		8	9	10	11	12	13	14
1	Project Work Continue	■	■	■					MID SEMESTER BREAK							
2	Submission of Progress Report 1				●											
3	Project Work Continue				■	■	■	■								
4	Submission of Progress Report 2									●						
5	Seminar (compulsory)										■	■	■			
5	Project work continue									■	■	■	■			
6	Poster Exhibition											●				
7	Submission of Dissertation (soft bound)													●		
8	Oral Presentation														●	
9	Submission of Project Dissertation (Hard															●

● Suggested milestone

■ Process

3.3 Work Flow chat

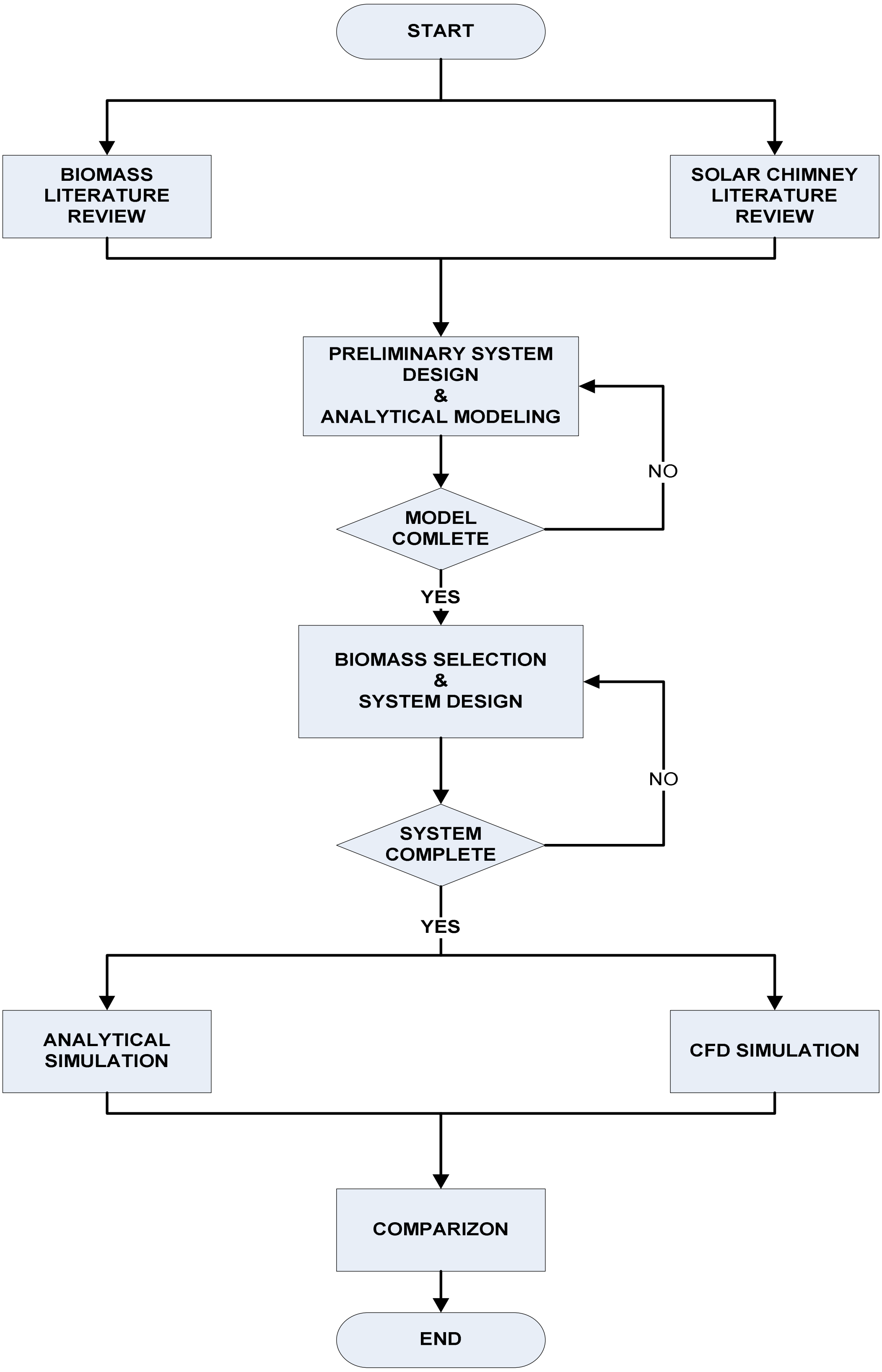


Figure 3: Work flow chat.

CHAPTER 4

MATHEMATICAL MODELING

Mathematical modelling is the mathematical representation of a system in order to study its behaviour under different conditions. The preliminary system design which includes only the drawing of the system, which is not drawn to scale for both cases, is shown in figures 1 & 2. The drawings show the basic idea of how the system will be. The material selection for components such as insulation, absorber and glass canopy material will be conducted after the system is finalized. The project is divided into two parts;

1. The first case is for a single flow stream to the Savonius rotor which is the flue gases only.
2. The second case is for the mixed flow of flue gases and air being directed to the on-roof rotor.

The present model is to find the velocity of the flue gases approaching the rotor and the amount of heat lost through the glass canopy. The mathematical model of the Savonius rotor will be covered at the beginning of next semester.

4.1 Mathematical modelling

Assumptions:

1. The flue gas behaves as an ideal gas.
2. No heat lost from the combustor to the inlet of the roof ($T_1 = T_2$).
3. The flue gas temperature change on the roof is small enough to neglect its reflection on the density.
4. The specific heat constants are uniform throughout the process.
5. The roof is symmetrical.

The heat transfer equations used in the following mathematical modelling were taken from Incropera and DeWitt.

4.2 Properties of the flue gases

The flue gas properties that are needed for the calculations are the density, specific heat, viscosity and heat transfer coefficient.

Flue gas density and specific heat were evaluated using the following general equation taken from Moran and Shapiro [4].

$$p = \sum_{i=\alpha}^{N} y_\alpha p_\alpha \; \dots \dots . . (1)$$

Where p is the species property either density or specific heat and y is the mass fraction of the species.

The viscosity and thermal conductivity of the mixture is approximated by [9];

$$p_{mix} = \sum_{\alpha=1}^{N} \frac{x_\alpha p_\alpha}{\sum_\beta x_\beta \phi_{\alpha\beta}} \; \dots \dots \dots \dots \dots \dots \dots \dots \dots . . \dots \dots . . (2)$$

$$\phi_{\alpha\beta} = \frac{1}{\sqrt{8}} \left(1 + \frac{M_\alpha}{M_\beta}\right)^{\frac{-1}{2}} \left[1 + \left(\frac{p_\alpha}{p_\beta}\right)^{\frac{1}{2}} \left(\frac{M_\beta}{M_\alpha}\right)^{\frac{1}{4}}\right]^2 \; \dots \dots . (3)$$

Where M is the species mole fraction and α is the species number. For equation 2 and 3, p can be the viscosity or the thermal conductivity of the species.

The flow is assumed to be turbulent and the heat transfer coefficient of the mixture is approximated using the following equation [12],

$$Nu_{mix} = \frac{h_{fg}.k}{\mu} = 0.023Re^{0.8}Pr^{n} \ldots\ldots\ldots\ldots\ldots\ldots\ldots..(4)$$

Where

$$Re = \frac{\rho.V_{avg}.D_h}{\mu} \ldots\ldots\ldots\ldots\ldots\ldots\ldots.(5),$$

$$\mathrm{Pr} = \frac{C_p.\mu}{k} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots..(6),$$

D_h is the hydraulic diameter of the roof and *n = 0.3* for cooling.

The properties were evaluated at a temperature of 300 ^{0}C and at a pressure of 1 atm for fruit branches, the analytical results were compared with the results from one of the software's used in Chemical Engineering called HYSIS and the error is around 0.2 - 0.3%.

4.3 CASE I

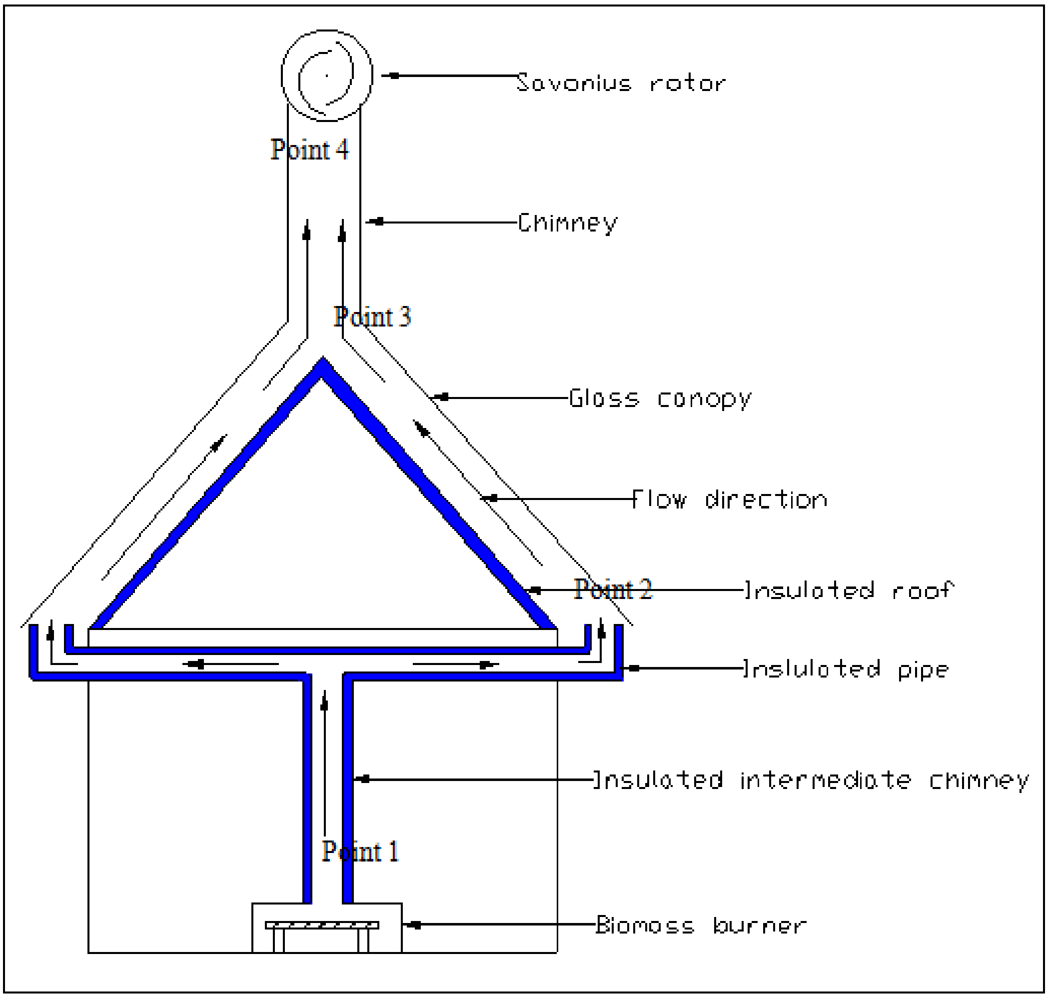


Figure 4: Preliminary system design for Case I.

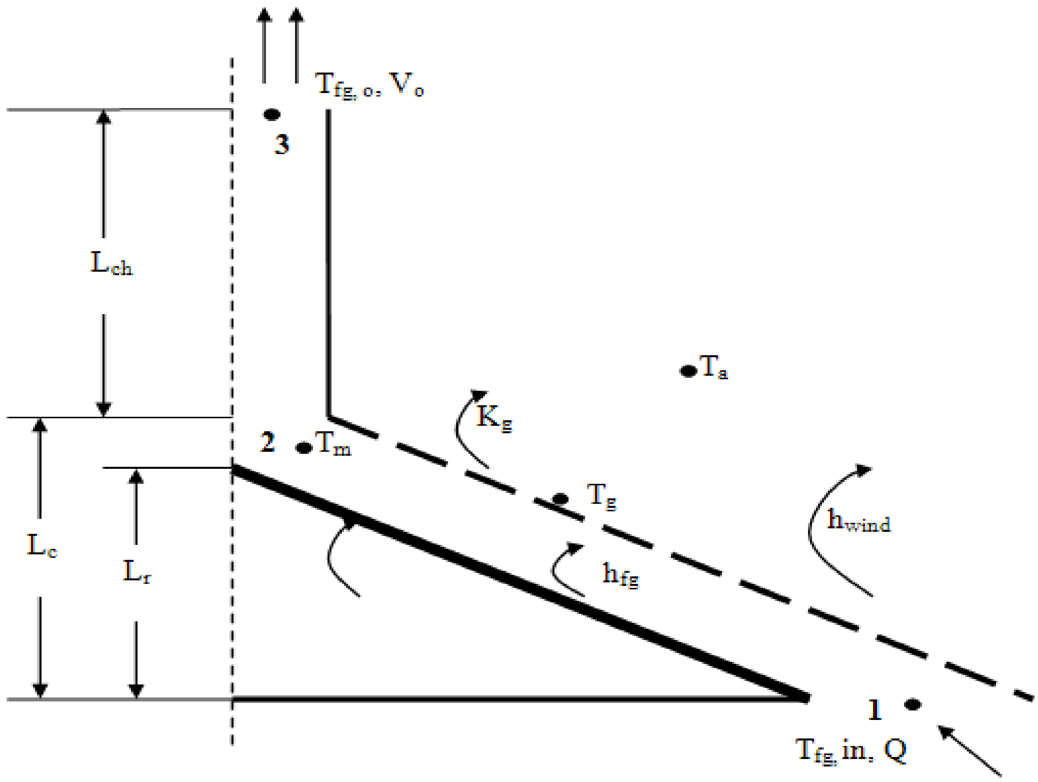


Figure 5: Physical Model of Case 1 of the on-roof solar chimney.

The inlet of the flue gases to the roof is considered for simulation based on the assumption mentioned earlier that the conditions in point 2 are the same as the conditions in point 1 for both Case 1 (Fig 5) and Case 2 (Fig 6)

The mass flow rate of the flue gases from the combustor (point 1) is given by,

$$\dot{m}_1 = \rho_{fg} V_{fg} A_{i,ch} \dots \dots \dots \dots (7)$$

Applying the continuity equation from point 1 to pint 3 we have;

$$\dot{m}_3 = \dot{m}_1 = \rho_{fg} V_3 A_{i,ch} \dots \dots . . (8)$$

Simplifying further and taking the velocity at point three as the subject of the equation we have;

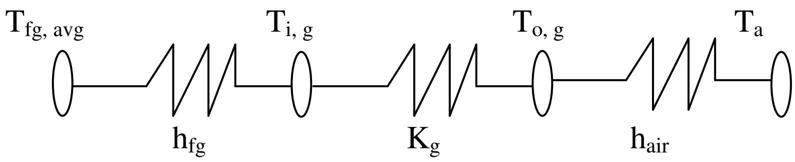
$$V_3 = \frac{\dot{m}_3}{A_{i,ch} \cdot \rho_{fg}} \dots\dots\dots\dots (9)$$

This is the stream velocity of the flue gases approaching the Savonius rotor.

The heat carried by the flue gases as they leave the combustor is given by;

$$\dot{Q}_{fg} = \dot{m}_{fg} c_{p,fg} T_{fg} \dots\dots\dots\dots (10)$$

The heat transfer to the ambient air is modelled as follows;



And is given by;

$$Q_{total} = \frac{T_{fg,avg} - T_a}{R_{tot}} \dots\dots\dots\dots (12)$$

Where $T_{fg,avg} = \frac{T_2+T_3}{2}$ and U the overall heat transfer coefficient is given by;

$$R_{tot} = \frac{1}{h_{fg} A_c} + \frac{L_g}{K_g A_g} + \frac{1}{h_{air} A_c} \dots\dots\dots\dots (13)$$

Where h_{fg} is taken as the transitional convection heat transfer coefficient for flue gases which is evaluated by

The energy balance from point 2 to 3 is given by the following thermodynamic equation;

$$\frac{dE_{cv}}{dt} = \dot{Q}_{cv} - \dot{W}_{cv} + \dot{m}\left(h_2 + \frac{V_2^2}{2} + gz_2\right) - \dot{m}\left(h_3 + \frac{V_3^2}{2} + gz_3\right) \dots\dots (14)$$

Assuming that;

- There's no rate of change of energy with time.
- Kinetic and potential energy changes are negligible.

Since there's no work done by the system we have;

$$-\dot{Q}_{cv} = \dot{m}_2(h_2 - h_3) \dots \dots \dots \dots (15)$$

Simplifying further in terms of the temperatures and making the temperature at point 3 the subject of the equation we have;

$$T_2 = \frac{2T_a + T_1(2\dot{m}_1 c_p R_{tot} - 1)}{(2\dot{m}_1 c_p R_{tot} + 1)} \dots \dots \dots .(16),$$

And the heat lost through the glass canopy is given by;

$$Q_{loss} = \frac{\left(\frac{T_1 + T_2}{2}\right) - T_a}{R_{tot}} \dots \dots \dots \dots .(17)$$

4.4 CASE II

Case two utilizes the heat lost through the glass canopy to heat the stream of air from the surrounding. This is achieved by placing an absorber material between the glass canopy and the roof. These two streams are later combined before entering the on-roof chimney. The mass flow rate and the velocity of the flue gases for point 1 & 2 are still the same as in Case I given by equation (7) and (8).

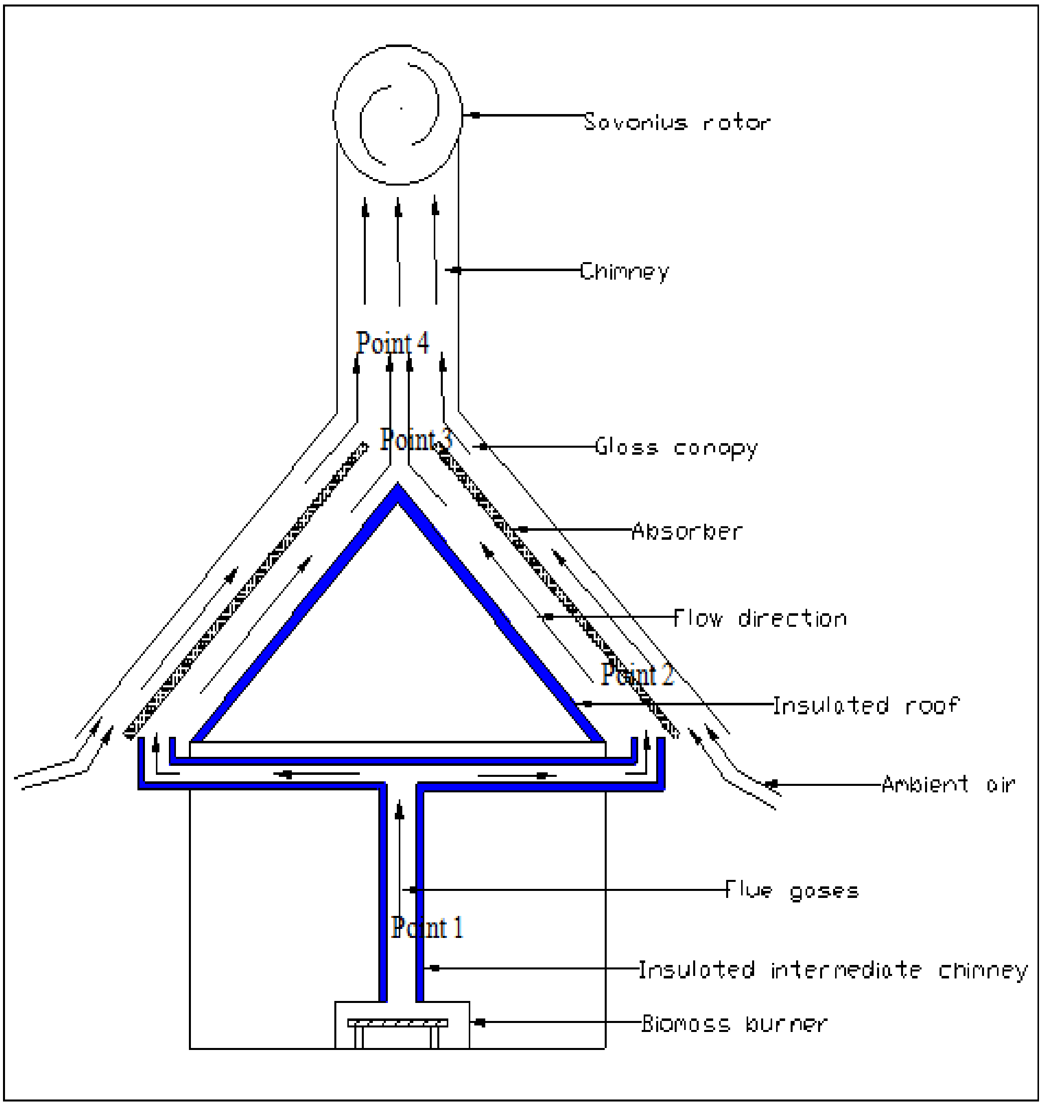


Figure 6: Preliminary layout of the system for Case II.

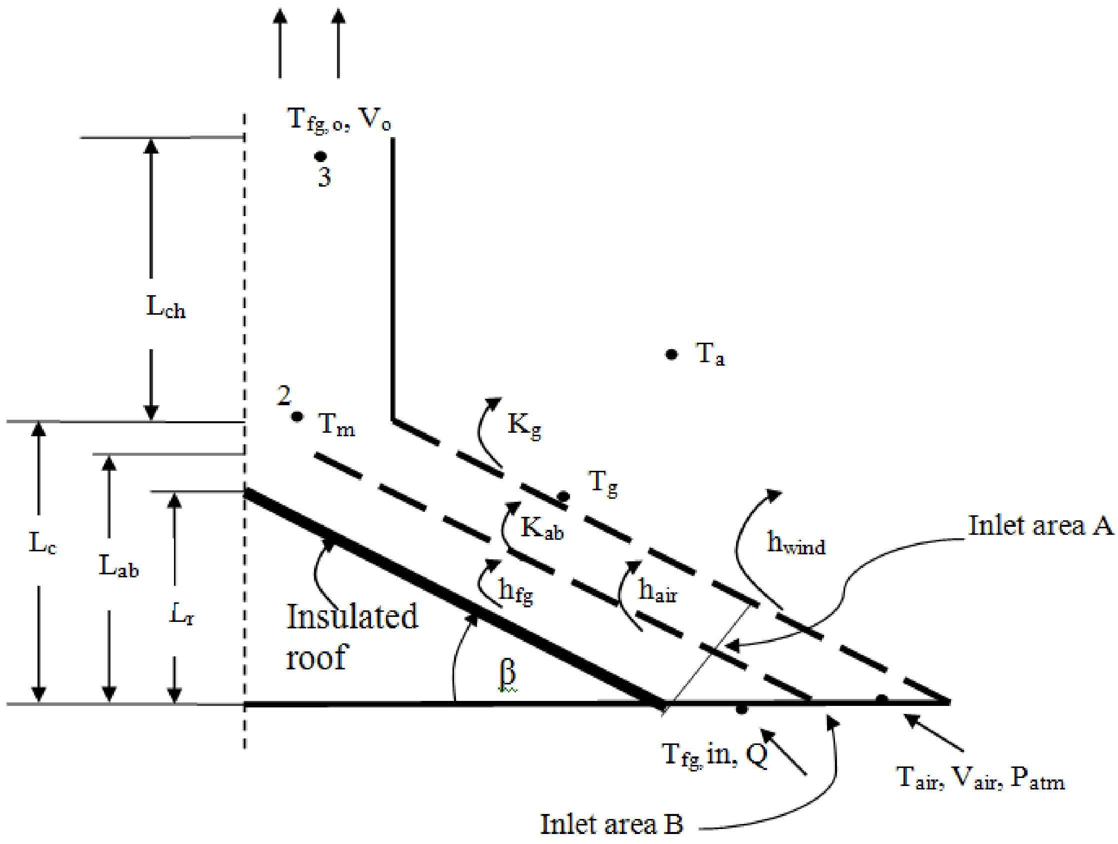
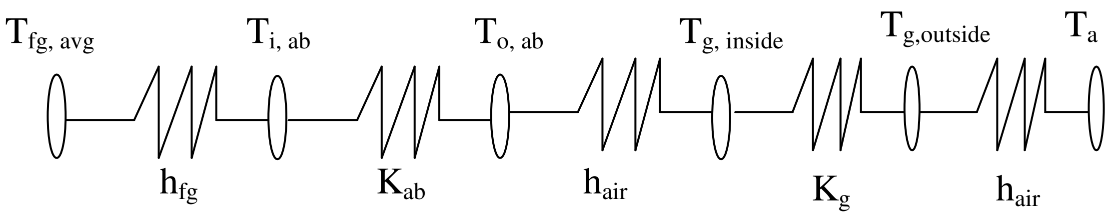


Figure 7: Physical model of Case II.

Assuming that the average wind velocity in Malaysia is 3 m/s, the mass flow rate of the air can be calculated using the following equation;

$$\dot{m}_{air} = \rho_{air} A_c V_{air} \dots \dots \dots \dots (18)$$

The heat transferred to the ambient air can be modelled as follows;



The overall heat transfer coefficient is of the form of equation (13) and is given by;

$$R_{tot} = \frac{1}{h_{fg}A_c} + \frac{L_{ab}}{K_{ab}A_{ab}} + \frac{L_g}{K_g A_g} + 2\frac{1}{h_{air}A_c} \dots\dots\dots (19)$$

Where the convection heat transfer coefficient for air can be approximated using the following equation;

$$h_{air} = h_{wind} = 2.8 + 3V_{wind} \dots\dots\dots\dots (20)$$

Using the continuity equation from point 2 to 3we have;

$$\dot{m}_3 = 2(\dot{m}_{2,a} + \dot{m}_{2,b}) \dots\dots\dots\dots\dots\dots\dots. (21)$$

Therefore the velocity of the combined streams is;

$$V_3 = 2\frac{(\rho_{fg}V_{1,a} + \rho_{air}V_{1,b}).A}{(\rho_{air} + \rho_{fg}).A_3} \dots\dots\dots\dots (22)$$

The heat lost by the flue gases is given by;

$$Q_{loss} = \frac{\left(\frac{T_{1,a} + T_{2,a}}{2}\right) - T_a}{R_{tot}} \dots\dots\dots\dots\dots\dots.. (23)$$

Temperatures of air and flue gases at point 2 of figure 7 are given by;

$$T_{2,a} = \frac{Q_{loss} - Q_{1,a}}{h_{fg}.A} + T_{1,a} \dots\dots\dots\dots\dots\dots\dots. (24), and$$

$$T_{2,b} = \frac{Q_{loss}}{h_{air}.A} + T_{1,b} \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots.. \dots\dots. (25)$$

Equation (22) gives the velocity of the mixture of air and flue gases that will run the Savonius rotor. The next report will cover the modifications of these equations, the modelling of the Savonius rotor, detailed design of the system and the biomass properties for calculations and simulation.

4.5 Power output

A Savonius wind turbine is used to generate electricity and is commonly used in free air stream environment. It is chosen for this application because it rotates at very low velocities depending on the rotor shape and size. A two blade rotor with a power coefficient of 0.3 is used for the analysis.

The power carried by the streams is given by the following equation;

$$P_{wind} = \frac{1}{2}\dot{m}V_3^2 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (27)$$

And the power generated by the turbine is approximated by the following equation;

$$P_{turbine} = C_p P_{wind} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots . \ldots\ldots (28)$$

CHAPTER 5

RESULTS

5.1 Analytical and CFD Results

Analytical calculations from the model were obtained using excel with the necessary data. The following table lists down some of the inlet conditions, outlet conditions, heat lost through the canopy and the pressure drop between the inlet and the out let. The results were obtained at two different inlet areas. Detail data that was used and the results are listed in the appendix for inlet area of $0.100\ m^2$.

Table 1: Analytical and HYSIS results of the Flue gas properties.

Property/Method	***Analytical***	***HYSIS***	***% Error***
Molecular mass (kg/kmol)	19.784	19.62	0.0829
Density (kg/m^3)	0.4166	0.4174	0.192
Viscosity (kg/m.s)	2.128E-05	1.847E-05	13.2
Thermal conductivity (W/m.K)	0.0589	0.05834	0.951

Table 2: Analytical and CFD Results for Case I.

Parameter	**Analytical**	**CFD**	**% Error**
Inlet conditions			
Area (m2)	0.05	0.05	0.0
Velocity (m/s)	5.00	4.900	2.0
Temperature (K)	573.15	569.16	0.696
Outlet conditions			
Velocity (m/s)	5.00	4.714	7.15
Temperature (K)	547.97	556.23	1.51
Heat loss (W)	-5704.0	-5992.4	5.06
Average canopy temperature (K)	560.56	546.37	2.53
Turbine Power output (W)	0.391	0.347	11.25

Table 3: Analytical and CFD results for CASE II.

Parameter	**Analytical**		**CFD**	
Inlet conditions				
	Air	Flue gas	Air	Flue gas
Area (m^2)	0.05	0.05	0.05	0.05
Velocity (m/s)	3.00	10.78	2.94	10.564
Temperature (K)	298.15	573.15	304.5	566.26
Outlet conditions				
Velocity (m/s)	5.00		4.924	
Temperature (K)	443.61		434.43	
Heat loss (W)	-4517.3		-4381.78	
Turbine Power output (W)	1.501		1.433	

5.2 CFD Results and Figures

Results obtained from FLUENT for a smaller area (*0.05* m^2) are in a form of graphs and contour plots for the temperature and velocity as follows;

Table 4: Area-Weighted Average Results.

Total Temperature	(Kelvin)
Canopy	546.37
Inlet	569.16
Outlet	556.23
Velocity	**(m/s)**
Inlet	4.900
Outlet	4.714
Heat lost	**Watts**
Through the canopy	-5992.41

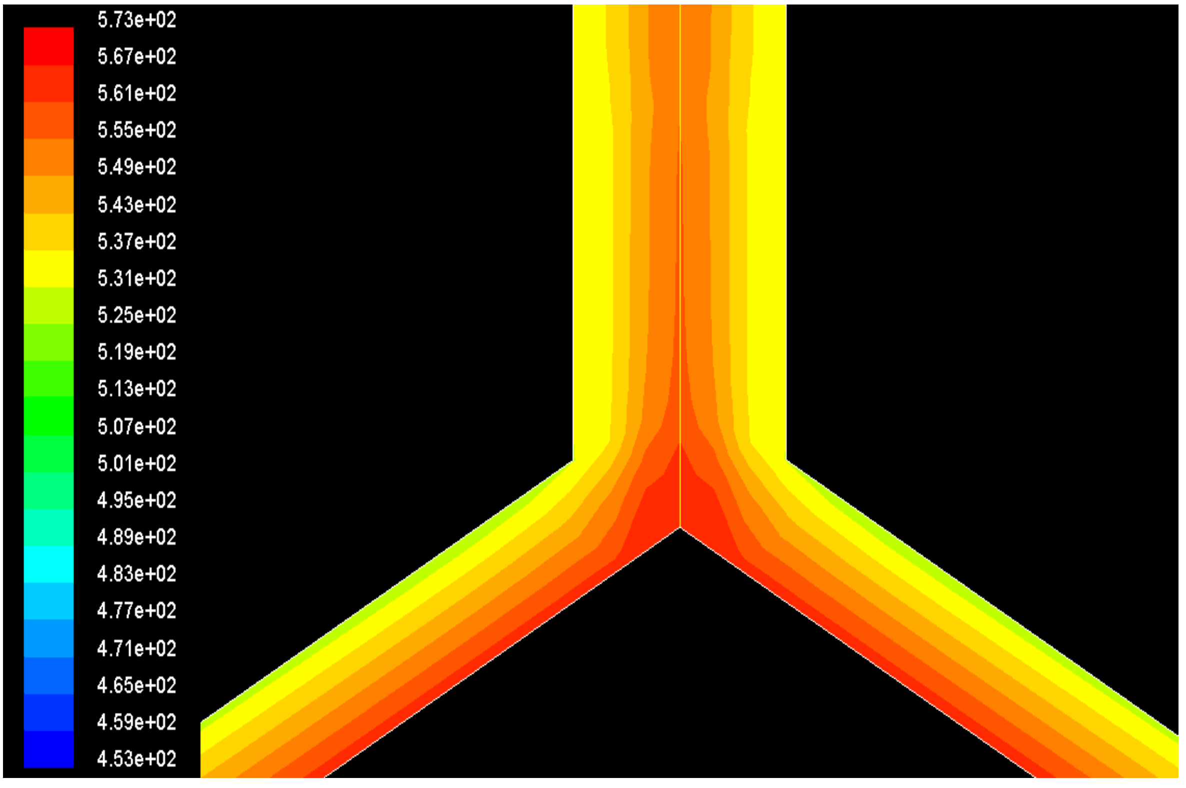


Figure 8: Temperature contours on the on-roof chimney.

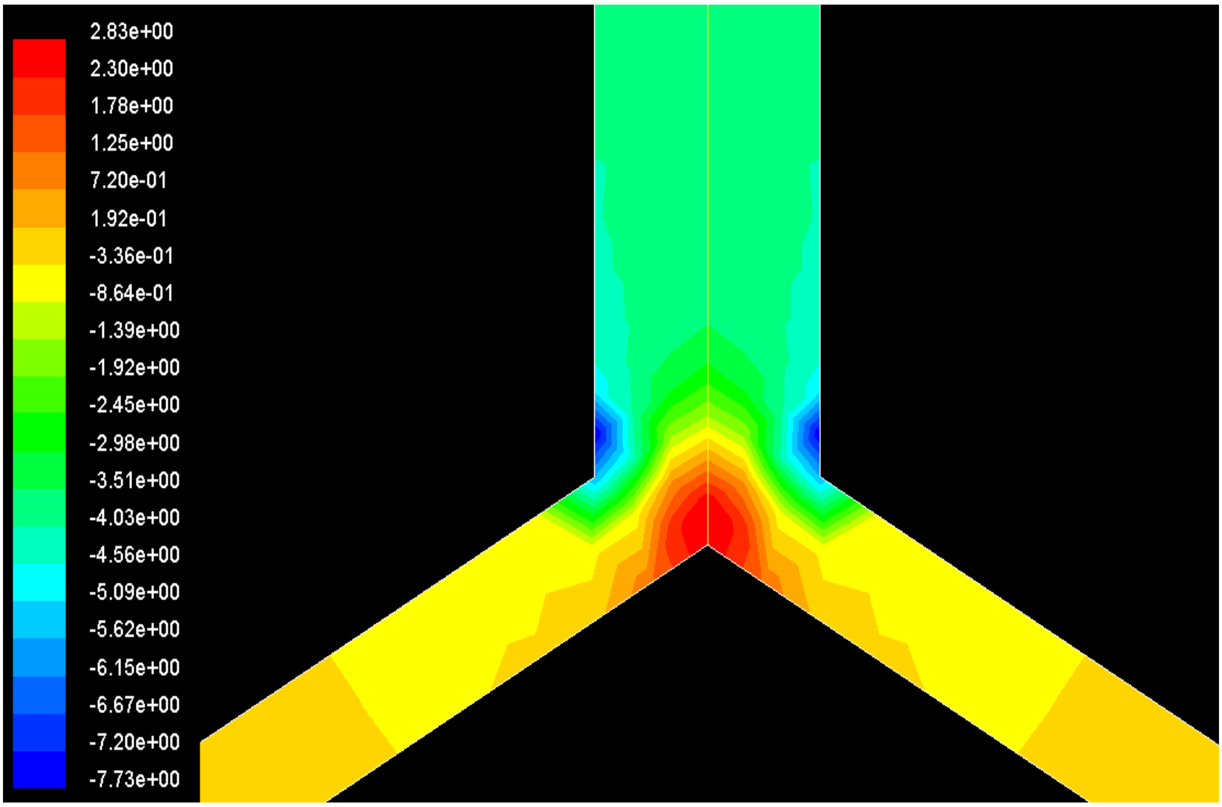


Figure 9: Static pressure contours.

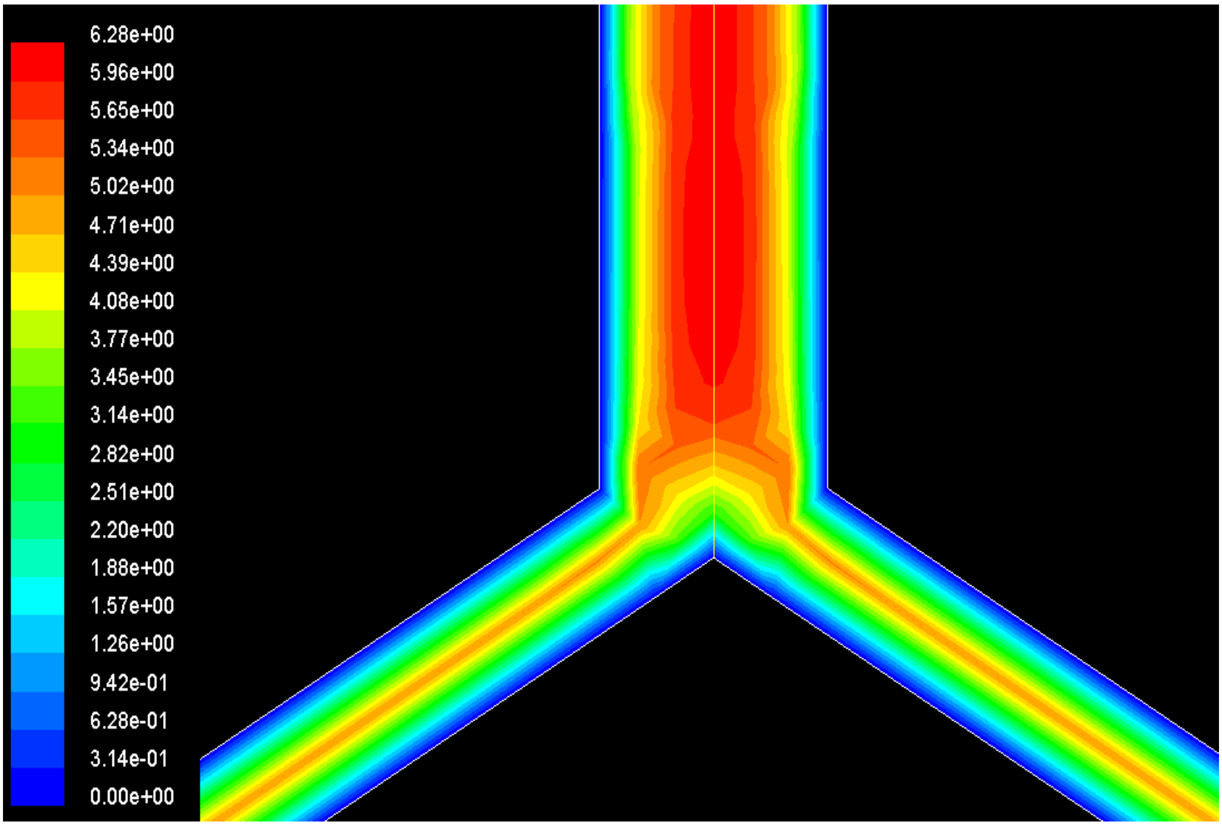


Figure 10: Contours of velocity magnitude (m/s).

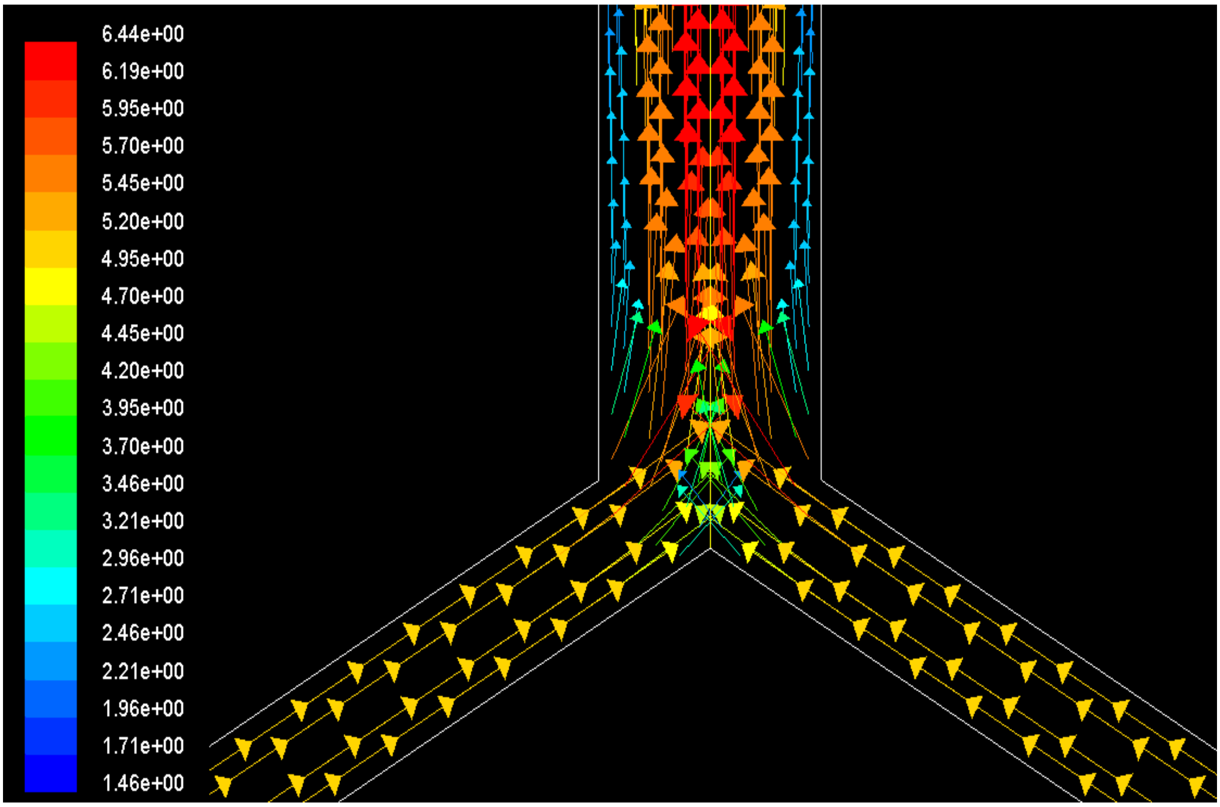


Figure 8: Velocity vectors colored by velocity magnitude (m/s) on the junction.

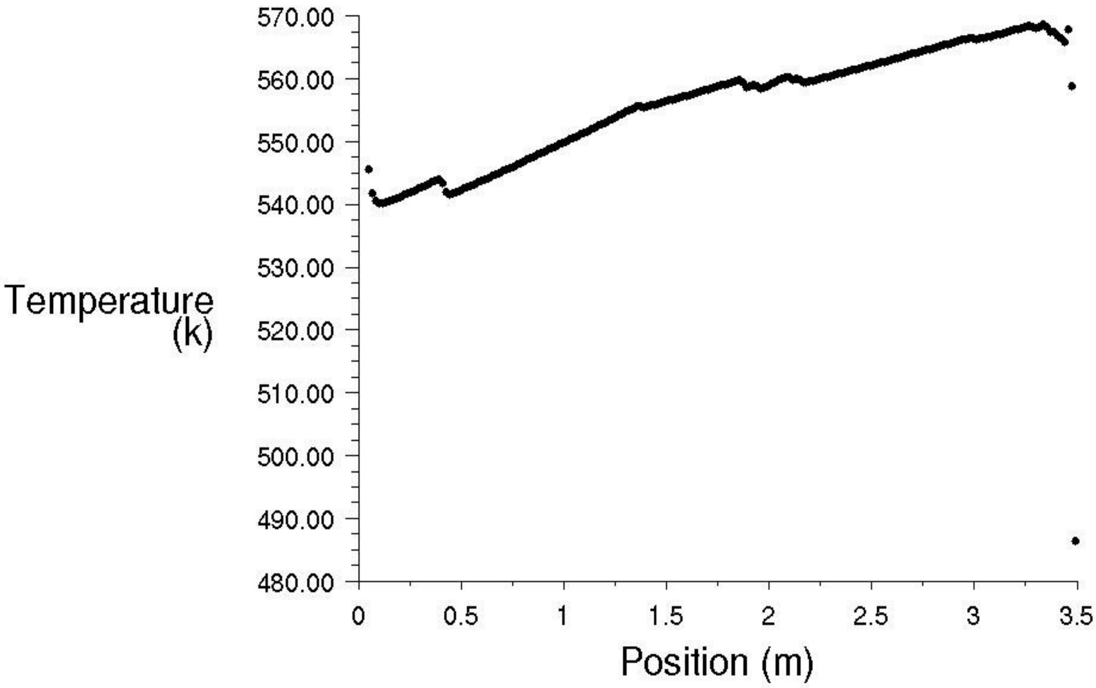


Figure 9: Temperature distribution along the length of the glass canopy.

5.3 Analytical results for different inlet areas for Case II.

Table 5: Case II results for different inlet areas.

Parameter	**Analytical**			
Inlet conditions				
	Air	Flue gas	Air	Flue gas
Area (m^2)	0.05		0.10	
Velocity (m/s)	3.00	10.78	3.00	1.079
Outlet conditions				
Velocity (m/s)	5.00		5.00	
Temperature (K)	443.61		422.517	
Heat loss (W)	-4517.3		-3534.6	
Turbine Power output (W)	1.501		1.501	

CHAPTER 6

DISCUSSION

From the analytical model we can see the average temperature of the canopy increases with the increase in inlet area by approximately 20 ^{0}C, the heat lost is also increasing together with the pressure drop, the inlet velocity and the temperature leaving the chimney is reduced due to the increase in the heat lost. The design velocity for the model is 5 *m/s* and reducing the inlet area increases the velocity and this will be further investigated to find the optimum inlet area together with the inlet velocity. A spreadsheet is attached in the appendix for the analytical calculations of case I with the larger area.

The temperature, pressure, velocity distributions in a form of contours are displayed in from figure 9 to 11. Temperature distribution along the length of the roof is shown in figure 12 and we can see that the temperature decreases along the roof. The maximum error between the analytical and CFD simulation is around 12 % which can be attributed to the losses due to the friction, bends, etc. that were not considered in the analytical model. Increasing the inlet area as shown in figure 7, shows that the same amount of power can be generated at a very low inlet velocity of the flue gases.

The turbine power output increases with the increase of the width house. The inlet velocity of the flue gases for CASE II is higher than the inlet velocity of the air which might not be practical in application. The velocity of the surrounding air is not always flowing in one direction and at constant speed this will affect the outlet velocity and thus the power output.

CHAPTER 7

CONCLUSION AND RECOMMENDATION

7.1 Conclusion

From the simulations it is shown that a significant amount of the heat carried by the flue gases leaves through the on-roof chimney and only 10% is lost through the canopy for Case I and the proposed Case II reduces the heat lost through the canopy by 3% which shows the potential to reduce the heat lost through the canopy by using a better and cheaper absorber material for Case II. The output power is increased by 74% per unit width of the house and it is shown that the power output increases with the width of the house.

The velocity of the flue gases in Case II can be lowered by using a fan to supply the air stream at required velocity. The analysis of the system proves that there is potential in using biomass to generate electricity for domestic applications. Further modifications to the roof dimensions' and the configuration of the Savonius wind rotor, and the type of biomass used will help optimize the system.

7.2 Recommendations

The study was only limited to a single type of biomass and also the dimensions of the house were not varied during the analysis, this provides an opportunity to further study the system in order to optimize it. The following recommendations are made based on the results obtained during the study;

- Vary the dimensions of the house for optimization
- Select an absorber that can further minimize the heat loss
- Simulate the system using different types of biomass waste
- Conduct an experiment to determine the mass flow rate of the flue gases
- Vary the air velocity (which in practical application can be achieved by using a fan) to find the minimum flue gas inlet velocity
- Fabricate a prototype to compare experimental with analytical and CFD simulations

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APPENDIX

Fuel	Proximate analyses (raw)				Ultimate analyses (waf)				
	Moisture	Volatile	FC[a]	Ash	C	H	O	N	S
Sunflower husk[b]	9.1	69.1	19.9	1.9	51.4	5.0	43.0	0.6	0.0
Cotton husk[b]	6.9	73.0	16.9	3.2	50.4	8.4	39.8	1.4	0.0
Mustard husk[b]	5.6	68.6	22.0	3.9	46.1	9.2	44.7	0.4	0.2
Palm fibre[b]	36.4	46.3	12.0	5.3	51.5	6.6	40.1	1.5	0.3
Pepper waste[b]	9.7	58.4	24.4	7.4	45.7	3.2	47.0	3.4	0.6
Soya husk	6.3	69.6	19.0	5.1	45.4	6.7	46.9	0.9	0.1
Groundnut shell[b]	7.88	68.1	20.9	3.1	50.9	7.5	40.4	1.2	0.02
Coconut shell[b]	4.4	70.5	22	3.1	51.2	5.6	43.1	0.0	0.1
Sewage sludge[c]	6.9	44.6	7.0	41.5	52	6.3	32.1	6.3	3.1
Coffee (mbuni) husks[c]	11.4	64.6	20.0	4.1	43.9	4.8	49.6	1.6	0.1
Coffee (parchment) husks[c]	10.2	72.0	17.0	0.9	46.8	4.9	47.1	0.6	0.6
Wood[c]	40.0	46.7	12.8	0.5	50.7	5.9	43.1	0.2	0.04
Peat[c]	37.0	41.0	17.7	4.3	57.1	5.9	43.1	2.3	0.8
Bituminous Coal[c]	7.5	34.0	53.6	4.9	88.0	6.0	4.0	1.2	0.8

[a] FC: fixed carbon.
[b] Source: Ref. [1].
[c] Measurements by the present authors.

Figure 10: Analysis of some agricultural and forest residues and coals.

CASE I: Spreadsheet

CASE I

Properties and Data

Species	Molar mass	No. moles	Molar mass X No. mol	Mole %	Mass %
	kg/kmol	kmol	kg/kmol	mol%	wt%
CH_4	16.0400	0.000220	5.0054	0.3121	0.2120
CO_2	44.0100	0.000080	4.9940	0.1135	0.0769
H_2O	18.0200	0.000380	9.7129	0.5390	0.7107
H_2	2.0160	0.000025	0.0715	0.0355	0.0003
Total	80.0860	0.000705	19.7838	1.0000	1.0000

Density, Specific Heat constants, Viscosity and Thermal Conductivity

Species	Density	Specific heat	Viscocity	Thermal Cond
	ρ (kg/m^3)	C_p (J/kg.K)	μ x10^{-5} (kg/m.s)	k (W/m.K)
CH_4	0.3411	3158	0.00001886	0.07996
CO_2	0.9358	1060	0.00002682	0.03814
H_2O	0.3831	1997	0.00002045	0.04345
H_2	0.04287	14481	0.00001403	0.2843
Mixture	0.41660	2175.3870	2.128E-05	0.0589

Specific heat constant (J/kg.K),	C_v =	1755.145
Temperature of flue gases (K),	T_{fg} =	573.15
Pressure of flue gases(kPa) ,	P_{fg} =	101.325
Gas constant (J/Kmol.K),	R =	8314
Ambient temperature (K),	T_a =	298.15
Velocity of the wind (m/s),	V_{wind} =	3.000
specific heat raion ,	C_p/C_v =	1.239

Viscosity and Thermal Conductivity Calculation Summary

α	β	M_α/M_β	μ_α/μ_β	$\phi_{\alpha\beta}$	$\sum x_\beta \phi_{\alpha\beta}$
1	1	1.00000	1.00000	1.00000	
	2	0.36446	0.70321	1.30856	1.02072
	3	0.89012	0.92225	1.01706	
	4	7.95635	1.34426	0.33755	
2	1	2.74377	1.42206	0.67821	
	2	1.00000	1.00000	1.00000	0.70927
	3	2.44229	1.31149	0.69961	
	4	21.83036	1.91162	0.19893	
3	1	1.12344	1.08431	0.98163	
	2	0.40945	0.76249	1.30284	1.00464
	3	1.00000	1.00000	1.00000	
	4	8.93849	1.45759	0.32344	
4	1	0.12569	0.74390	1.99787	
	2	0.04581	0.52312	2.27172	1.98578
	3	0.11188	0.68606	1.98344	
	4	1.00000	1.00000	1.00000	

Prandlt number, Pr = 0.7854
Raynolds Number, Re = 9322.686
Hydraulic diameter, D_h = 0.0952
Nusselt Number, Nu = 32.055

Heat transfer coeffient of the flue gases ($W/m^2.K$), h_{fg}= 19.836
Heat transfer coeffient of air ($W/m^2.K$), h_{air} = 11.800
Glass thermal donductivity (W/m.K), k_g = 1.4000
Overall heat coefficient (K/W), R_{tot} = 0.04601
Outlet velocity (m/s), V_3 = 5.000
Glass canopyThickness (m), t_g = 0.004
Height of the chimney (m), L_{ch} = 2.500
Width of the roof (m), w = 1.000
Inclination of the roof (^{0}), θ = 30.000
Height of the roof (m), L_r = 1.500

Gap b|w glass and roof (m)	t_{rg} =	0.050
Chimney opening (m),	t_{ch} =	0.050
Glass canopy length (m),	l_g =	3.000
Roof length (m),	l_r =	3.000

Calculations

Area of the glass canopy (m^2),	A_g =	3.000
Inlet Area(m^2),	A_{rg} =	0.050
Outlet area (symmetry) (m2),	$A_{ch,o}$ =	0.050
Outlet mass flowrate (kg/s),	m_3 =	0.104
Inlet mass flowrate (kg/s),	m_1 =	0.104
Inlet velocity (m/s),	V_1 =	5.000
Temperature at point 2 (K),	T_2 =	547.974
Temperature at point 3 (K),	T_3 =	547.974
Heat carried by flue gases (W),	Q_{fg} =	129855.405
Heat lost through glass canopy (W),	Q_{loss} =	5703.986

Theoretical Power output

Power coefficient	C_p =	0.3
Stream power (W),	P_{wind} =	1.3019
Turbine power (W),	$P_{turbine}$ =	0.3906

CASE II: Spreadsheet

CASE II

Properties and Data

Species	Molar mass	No. moles	Molar mass x No. mol	Mole %	Mass %
	kg/kmol	kmol	kg/kmol	mol%	wt%
CH_4	16.0400	0.000220	5.0054	0.3121	0.2120
CO_2	44.0100	0.000080	4.9940	0.1135	0.0769
H_2O	18.0200	0.000380	9.7129	0.5390	0.7107
H_2	2.0160	0.000025	0.0715	0.0355	0.0003
Total	80.0860	0.000705	19.7838	1.0000	1.0000

Density, Specific Heat constants, Viscocity and Thermal Conductivity

Species	Density	Specific heat	Viscocity	Thermal Cond
	ρ (kg/m^3)	C_p (J/kg.K)	μ x10^{-5} (kg/m.s)	k (W/m.K)
CH_4	0.3411	3158	0.00001886	0.07996
CO_2	0.9358	1060	0.00002682	0.03814
H_2O	0.3831	1997	0.00002045	0.04345
H_2	0.04287	14481	0.00001403	0.2843
Mixture	0.41660	2175.3870	2.128E-05	0.0589

Flue gases

Specific heat constant (J/kg.K), C_v = 1755.145

Temperature of flue gases (K), T_{fg} = 573.15

Pressure of flue gases(kPa) , P_{fg} = 101.325

Specific heat ratio , C_p/C_v = 1.239

Air

Ambient temperature (K), T_a = 298.15

Air inlet density (kg/m^3), $\rho_{1,b}$ = 1.184

Air specific heat capacity (J/kg.K), $C_{p,b}$ = 1007

Air viscosity (kg/m.s), μ_{air} = 1.8490E-05

Velocity of the wind (m/s), V_{wind} = 3.000

Constant

Gas constant (J/Kmol.K), R = 8314

Viscosity and Thermal Conductivity Calculation Summary

α	β	M_α/M_β	μ_α/μ_β	$\Phi_{\alpha\beta}$	$\sum x_\beta \Phi_{\alpha\beta}$
1	1	1.00000	1.00000	1.00000	
	2	0.36446	0.70321	1.30856	1.02072
	3	0.89012	0.92225	1.01706	
	4	7.95635	1.34426	0.33755	
2	1	2.74377	1.42206	0.67821	
	2	1.00000	1.00000	1.00000	0.70927
	3	2.44229	1.31149	0.69961	
	4	21.83036	1.91162	0.19893	
3	1	1.12344	1.08431	0.98163	
	2	0.40945	0.76249	1.30284	1.00464
	3	1.00000	1.00000	1.00000	
	4	8.93849	1.45759	0.32344	
4	1	0.12569	0.74390	1.99787	
	2	0.04581	0.52312	2.27172	1.98578
	3	0.11188	0.68606	1.98344	
	4	1.00000	1.00000	1.00000	

Prandlt number, Pr = 0.7854

Raynolds Number, Re = 14621.852

Hydraulic diameter, D_h = 0.0952

Nusselt Number, Nu = 45.948

<u>Heat transfer coefficients</u>

Heat transfer coeffient of the flue gases ($W/m^2.K$), h_{fg}= 28.434

Heat transfer coeffient of air ($W/m^2.K$), h_{air} = 11.800

Glass thermal donductivity (W/m.K), k_g = 1.4000

Absorber thermal conductivity (W/m.K), K_{ab} = 222.00

Overall heat coefficient (K/W), R_{tot} = 0.05984

Outlet velocity (m/s), V_3 = 5.000

Width of the roof (m), w = 1.000

Inclination of the roof (^{0}), θ = 30.0

Height of the chimney (m),	L_{ch} =	2.000

Glass canopy

Glass canopyThickness (m),	t_g =	0.004
Height of the canopy(m),	L_g =	1.500
Glass canopy length (m),	l_g =	3.000

Roof

Height of the roof (m),	L_r =	1.9134
Roof length (m),	l_r =	3.827

Absorber

Absorber thickness (m),	t_{ab} =	0.001
Heigth of the absorber (m),	L_{ab} =	1.9567
Absorber length (m),	l_{ab} =	3.9134

Openings

Gap b|w glass and roof (m)	t_{rg} =	0.050
Chimney opening (m),	t_{ch} =	0.050