DESIGN AND THERMODYNAMIC ANALYSIS OF SOLAR UPDRAFT TOWER

by

BABALEYE O. AHMED

A Thesis Report Submitted to the Department Of Mechanical Engineering in partial fulfilment of the requirement for the award of the degree of

Bachelor of Engineering in Mechanical Engineering

at the

UNIVERSITY OF APPLIED SCIENCES, SCHMALKALDEN
JUNE 2011

Author...

Certified by: ....
PROF. Dr.-Ing. Robert Pietzsch

Certified by: ....
PROF. Dr.-Ing. Frank Beneke

CANDIDATES DECLARATION

I hereby declare that this project titled "Design and Thermodynamic Analysis of Solar Updraft Tower" submitted in partial fulfilment of the award of bachelor of engineering in the final semester to the faculty of engineering, department of Mechanical Engineering at the University of Applied Sciences, Schmalkalden is an authentic record of my work carried out under the supervision of Professor Dr. Robert Pietzsch, University of Applied Sciences Schmalkalden Germany.

Signature: ....

Babaleye Ahmed Oyeyinka (301043)

Place: UAS, Schmalkalden Germany.

Date: 30.06.2011

BONAFIDE CERTIFICATE

This is to certify that the above declaration made by Mr. Babaleye Ahmed is true to the best of my knowledge and belief.

Date:

Place: University of Applied Sciences Schmalkalden, Germany.

Professor Dr.-Ing. Robert Pietzsch

Professor Dr.-Ing. Frank Beneke

University of Applied Sciences, Schmalkalden

Germany.

ACKNOWLEDGEMENT

First and foremost, my unconditional thanks to God Almighty (the highest of all) for providing me with the strength to follow this project from genesis to a meaningful revelation.

Moreover, I am heartily thankful to my supervisor, Professor Dr.-Ing. Robert Pietzsch, whose consistent encouragement, guidance and support from initial to the final level enabled me to develop a thorough understanding of the project.

I owe a great deal of gratitude to the manufacturing technologists and laboratory technicians, especially Mr. Peter Wetzel, of UAS Schmalkalden and the rapid prototyping machine programmer.

Lastly, I offer my humble regards and blessings to all of those who supported me in any respect during the completion of the project.

Babaleye Ahmed Oyeyinka.

ABSTRACT

Solar updraft towers is a robust green energy plant that produce electricity based on a relatively simple but proven method of harnessing the energy of the sun to an air collector, which acts like a green house heat exchanger. It is a solar thermal power plant consisting of an air collector (green house), a central updraft tower for generating solar induced convective flow and a turbine unit driven by the heat transfer fluid, HTF entrapped beneath the green house, to produce energy in the form of electricity.

This paper presents the thermodynamic analysis of an educational prototype, analyze the fluid flow across the tower both in the ideal and real case, radiation optimization of the greenhouse heat exchanger and evaluate the possible humidification effect around the heating zone. First, the thermo-fluid theory of the wind turbine and solar tower is described. Then, results from the modelled design, simulation using CFD and characteristic curves are presented. Consequently, Recommendations for future and on-going solar tower projects are offered.

Keywords: Solar thermal power plant, Greenhouse heat exchanger, solar induced convective flow, Heat transfer fluid, HTF.

TABLE OF CONTENTS

TITLE **PAGE**

LIST OF FIGURES

TITLE **PAGE**

LIST OF TABLES

TITLE **PAGE**

SYMBOLS, NOMENCLATURE AND ABBREVIATIONS

H........................	Geodetical height of the tower [m]
d........................	Diameter of the tower [m]
D.........................	Diameter of solar collector [m]
g.........................	Acceleration of free-fall due to gravity [ms^{-2}]
w........................	Velocity of air [ms^{-1}]
u.........................	Peripheral velocity of turbine blades [ms^{-1}]
h_e.......................	Greenhouse entrance height [m]
A_c.......................	Solar collector cross-sectional area [m^2]
A_o.......................	Tower cross-sectional area [m^2]
h_f........................	Head loss due to friction [J]
h_o........................	Enthalphy at dead state [J]
h_u........................	Enthalpy at elevated temperature state [J]
T_o.........................	Outside temperature (Dead state) [K]
T_u.........................	Temperature inside greenhouse heat exchanger [K]
P_o.........................	Pressure outside the tower [Pa]
P_u.........................	Atmospheric pressure inside heat exchanger [Pa]
$\dot{m}$.........................	Air mass flow [Kgs^{-1}]
$\dot{m}_{opt}$...................	Optimum mass flow [Kgs^{-1}]
$\dot{V}$..........................	Volumetric flow of air [m^3s^{-1}]
$\dot{P}$..........................	Turbine power output [Js^{-1}]
$\dot{P}_{max}$....................	Maximum power of turbine [Js^{-1}]
S_r.........................	Sunrise time [hours]
S_s.........................	Sunset time [hours]
t.............................	Time of the day [hours]
$\dot{I}^d$..........................	Direct solar irradiance [Wm^{-2}]
$\dot{I}_h$..........................	Surface Insolation (Horizontal solar intensity) [Wm^{-2}]
$\dot{G}$..........................	Global radiation [Wm^{-2}]
$\boldsymbol{E}$..........................	Surface Irradiance of the Sun (Without hindrance) [Wm^{-2}]
ϵ...........................	Emissivity of the Sun
α............................	Absorptivity of the collector
τ...........................	Transmitivity of the collector
T_r........................	Opacity of the atmosphere

λ_{max}....................	Peak wavelength of sunlight [m]
R...........................	Radius of the Sun (6.96 x 10^5 km)
r............................	Average Sun-Collector distance (1.5 x 10^8 km)
ϕ..........................	Time angle [degrees]
φ..........................	Solar declination angle [degrees]
γ..........................	Adiabatic constant
C_p........................	Specific heat capacity of air at constant pressure [$KJ.kg^{-1}k^{-1}$]
C_v........................	Specific heat capacity of air at constant volume [$KJkg^{-1}k^{-1}$]
β..........................	Latitude
κ..........................	Isentropic exponent
ψ..........................	Zenith angle [degrees]
δ...........................	Differential change
ξ...........................	Roughness co-efficient [dimensionless]
ν.......................	Kinematic viscosity of air [m^2s^{-1}]
λ...........................	Friction/Resistance co-efficient [dimensionless]
ΔP........................	Pressure drop [Pa]
ω..........................	Angular velocity [rads/s]
x...........................	Turbine tip-speed ratio [dimensionless]
μ_t..........................	Time reduction factor [ ]
N_s..........................	Geometrical orientation [degrees]
ε.............................	Turbine power co-efficient [%]
B.............................	Exponential Constant of proportionality
K.............................	Relationship Constant
σ.............................	Steffan-Boltzmann constant [$Wm^{-2}K^{-4}$]
η_c............................	Carnot efficiency [%]
η_{conc}......................	Solar concentrator efficiency [%]
η_{th}..........................	First-law thermal efficiency [%]
η_{II}...........................	Second-law efficiency [%]
T_n............................	Time of the year [hours]
ϖ............................	Absolute/Specific humidity [%]
$\emptyset$	Relative humidity [%]
SFEE........................	Steady Flow Energy Equation
ROI..........................	Return On Investment

CHAPTER ONE
1.1 INTRODUCTION

1.1.1 General

The notion of going green is not strictly a new technological concept, and any naturally occuring and theoretically inexhaustible energy such as wind, biomass, solar, tidal, wave, hydroelectric power that is not derived from fossil or nuclear fuel is referred to as renewable energy. The relevance of these emerging field became more pronouced when the need to produce clean, safe and efficient energy devices without trading off environmental friendliness arise.

A typical Solar Updraft Tower Plant (SUTP) consists of a circular greenhouse type collector and a tall tower (chimney) at its centre. Air flowing radially inwards under the air collector is heated from the collector floor and roof, and through a turbine enters the chimney. Thereby staging a pressure build up along the tower, and the heat transfer fluid, HTF is warmed up in order to drive the turbine, hence produces energy in the form of electricity.

The idea of using solar radiation to generate air convection that can subsequently be converted to an energy source has been around since the start of the 20th century, when a Spanish Colonel called “Isidoro Cabanyes”, proposed it in a scientific magazine. Solar Updraft towers, also called solar wind or solar chimney plants, provide a very simple method for renewable electricity generation, with a constant and reliable output. Other renewable energy sources such as wind turbines and solar arrays suffer from high diurnal and seasonal fluctuations, or unpredictable patterns of output.

Sensible technology for the wide use of renewable energy must be simple and reliable, accessible to the technologically less developed countries that are sunny and often have limited raw materials resources. It should not need cooling water and should be based on environmentally friendly production from renewable or recyclable materials. Invariably, solar updraft tower meets these requirements. A typical pictorial illustration of the robust set up and technology behind the solar updraft tower is shown in figure 1.1 below.

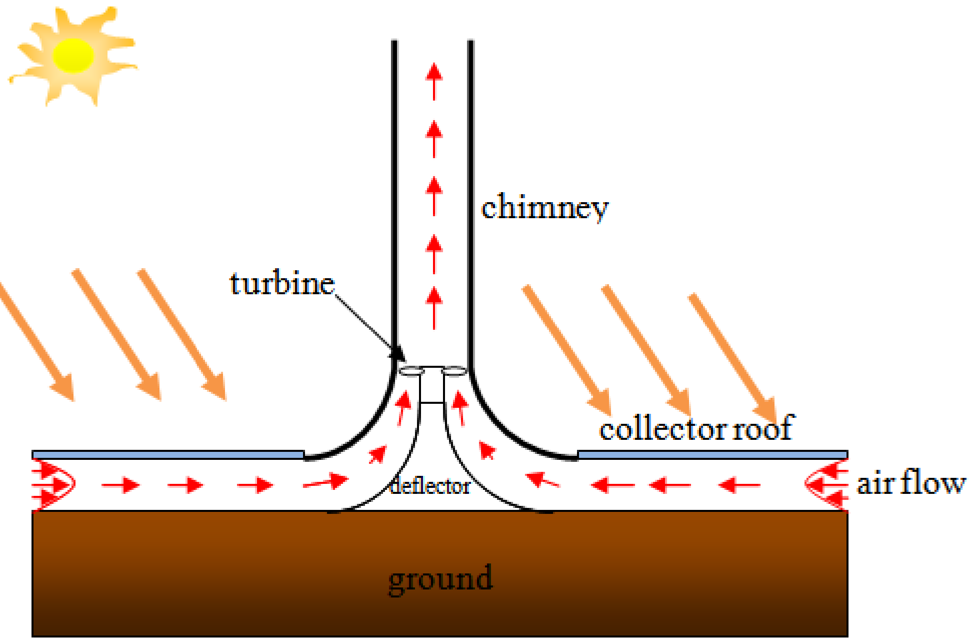

Figure 1 Schematic of the solar updraft tower. **Sources: MEF[1]**

1.1.2 Overview

From earliest times, humans have actively made use of solar energy: Greenhouses aid in the cultivation of food crops, the chimney updraft was employed for ventilation and cooling of buildings, and the turbo-machinery for grinding grains, pumping water and driving generators. The three essential components of a Solar Updraft Tower power plant being;

i. A hot air collector

ii. A Chimney or tower and,

iii. A wind turbine.

Current electricity production from fossil fuels like natural gas, oil and or coal are by and large, environmentally unfriendly. Thus, because they bear the limitations that rely on non-renewable energy sources. Many developing countries cannot afford these conventional energy sources, and

[1] Solar-Updraft-Tower

in some of these locations nuclear power is considered a threat or more or less an unacceptable risk. No doubt, poverty girders the bridge between lack of energy and population explotions. The need for an environmentally friendly and cost effective electricity generating scheme is invariably obvious and would be more alarming in the nearest future.

A proven remedy to the ever-increasing energy production problem is Solar Energy. It is inexhaustible and abundant renewable source of energy that only needs to be harnessed to be utilized by man. Solar power plants in use in the world are modelled to transform solar irradiation into electrical energy through any one of a number of cycles or natural phenomenon. A number of solar power plants have the ability to encase or store sufficient energy during the day in order that, it can be used at night when there is no sunlight. However, the practical viability of these storage capacity are seemingly too high. Figure 2 below, shows the regions and continents where this ever-booming technology is of utmost relevance.

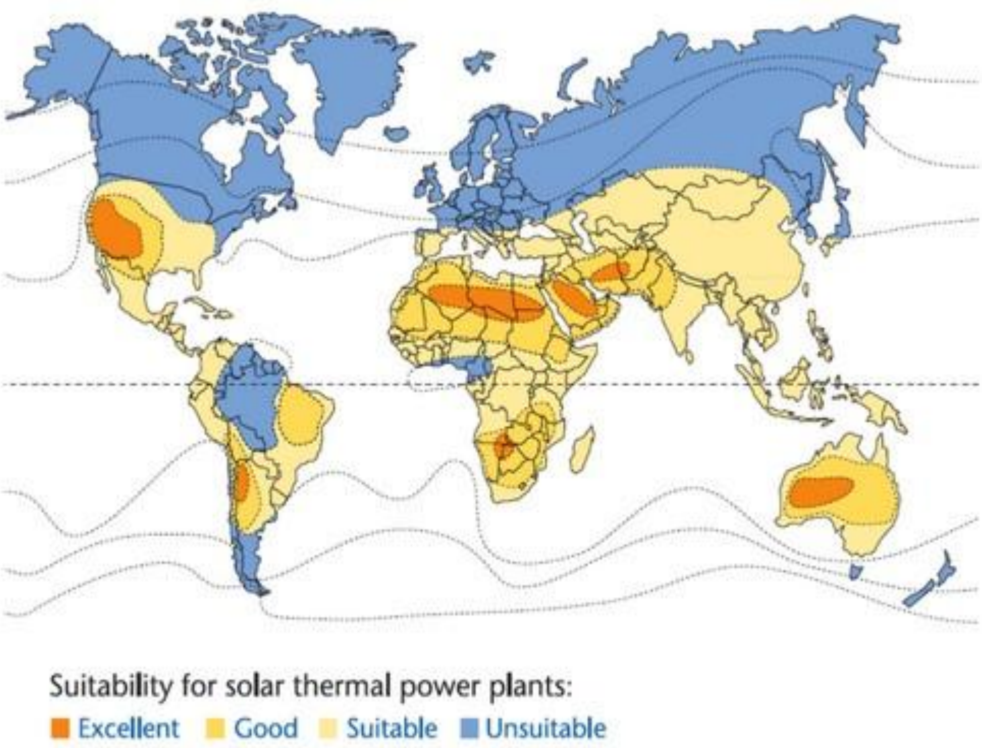

Figure 2 Continents of relevance. Sources: katharine hamnett[2]

[2] www.katharinehamnett.com.

1.1.3 Thesis Problem Statement

The basic relevance of this simple and proven technology is obvious and will continue to attract excellent research talents around the world. In fact, the need for solar technology cannot be over-emphasized in this 21st century. It has been said earlier that, the technology combines three practical robust components, viz; the solar collector (green house), the solar tower and the wind turbine. All of which are assembled in such a way that they function as a single energy generation unit. Thorough researches, accompanied by extensive wind tunnel experiments, show that thermodynamic analysis for the collector, tower and turbine are quite reliable and consistent for all plants, irrespective of it sizes (Schlaich et al. 1990).

The thermodynamic calculations of this plant has proven to be consistent over time, although there are sizable number of shortcomings in its optimization and design. It is obvious that, to raise the efficiency of this plant, the tower height must be as high as possible, this is by and large, an aspect that calls for on-going and future research improvement. Thus, A high tower requires advance manipulation of stress analysis and proficient solid mechanics and adequate material selection skills. Consequently, The solar irradiation often strikes the solar collector at an angle whose magnitude is not easily accessible. In addition, various research findings has shown that only a few proportion of the sunlights' energy reaches the collector as some of it would have been diffused before reaching it. Another important aspect is that of the cost of operation and maintenance, although, a good design does not require much maintenance cost. The investment cost is on the high side, since a good solar tower works best when the greenhouse (solar collector) has as large diameter as possible. This implies that much area of land is required to set up this robust and green power plant.

However, it is evident that the maximum power, $\dot{P}$ output of the turbine depends largely upon the inlet velocity, w_1 of the heated air entering the tower.

Additionally, the research is based on designing an educational model in order to carefully estimate the parameters of this plant using basic flow mechanics and thermodynamic theory.

Invariably, another important requirement of this study is to design the turbine unit in a way it can function at its best. This can be achieved by applying the profound knowledge of flow mechanics.

1.1.4 Thesis Purpose

The purpose of this study is to evaluate by how much the inlet velocity, w_1 of air varies with the;

i. Output power , $\dot{P}$ of the wind turbine
ii. Diameter, D of the collector
iii. Zenith angle, ψ
iv. Entrance height, h_e
v. Geodetical tower height, H and
vi. Diameter of the tower, d

And also, Analyze the power plant using proven thermodynamical laws and compare the results with that obtained from the modelled prototype.

1.1.5 Research Questions

i. What are the different possible practical applications of the solar updraft tower?
ii. What kind of variations exist in recent installations?
iii. How can the thermodynamical model be derived based on energy, mass and impulse balance equations?
iv. How can the turbine unit be designed with respect to principles of flow mechanics?
v. What is the influence of the air humidity and possible humidification effects in the heating zone?

1.1.6 Design Components

Since this research is based upon designing an educational model and analyzing its thermodynamics, hence, we have used a number of mechanical parts in our assembling, electrical heating elements instead of solar heat and a fan-anemometer in place of wind turbine. The main parts used in the set up are listed, thus;

i. Aluminium base with dimension 1000mm by 600mm on ground with heating element mounted on an insulator.
ii. Polyvinylchloride (PVC) pipe, coloured in close proximity to a black-body, about $2m$ and $160mm$ diameter.
iii. DC stepped motor with rapid prototyped propeller (12v/12A).
iv. Fan anemometer.
v. Large transparent plexiglass canopy to serve as solar collector heat exchanger.
vi. Mechanical fasteners and screw, clamps, nails, strings etc to fasten and construct the whole set-up.

1.2 Concept Of Solar Energy

Solar energy is the energy that originates from the thermonuclear fusion reactions occuring in the sun. It is thus, an embodiment of the entire electromagnetic radiation (Visible light, infrared, ultraviolet, x-rays and radio waves).

It however, has the greatest potential of all the sources of renewable energy. The features and composition of the sun can be well perceived from the figure 1.3 (a and b), below. The solar energy provides the power plant the needed input energy in the form of heat, that is extracted from the sun by the solar collector. The wavelength of this solar irradiance bears an inverse relation to the maximum available global radiation in the presence of atmospheric impurities and weather effects. It would be shown in later sections that, the amount of radiation sufficient enough to drive the cold air beneath the solar collector is indeed a the sum of all possible types of radiation, such as;

i. Direct radiation
ii. Diffuse radiation and,
iii. Reflective radiation.

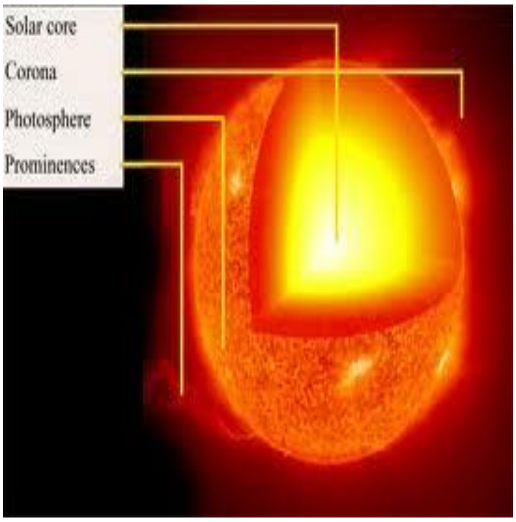

Figure 3 Component of sun's light

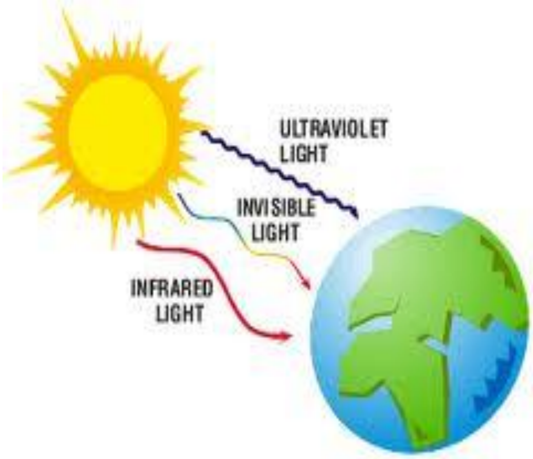

Figure 4 Structure of the Sun. Sources: fullwiki[3]

1.2.1 Merits Of Solar Energy

i. The solar irradiation reaching the earth is entirely pure. This is because, all chemical and radioactive polluting byproducts of the thermonuclear reactions remain behind the sun.

ii. The proportion of energy reaching the earth is sufficiently larger than the energy equivalent of the total of all the planest's fossil fuels, both used and unused.

iii. Utilizing solar energy to generate electricity is one of the greatest achievements by mankind, and is set for even greater things in the future.

iv. The technology behind a solar energy utilization is simple and reliable.

v. The cells have a high life-span with very little maintenance.

[3] Electromagnetic wave of light.

vi. The relatively low-technology approach could allow local resources and labour to be used for its construction and maintenance.

1.2.2 Demerits Of Solar Energy

i. Sun does not shine consistently, even in the tropical countries, due to several circumstances.

ii. Solar energy is a diffuse source, which means, only a proportion of it is usually trapped efficiently by the solar collector.

iii. The initial investment and capital cost of equipment used to harness the sun's energy.

iv. Installing a solar energy requires large area for the system to be efficient in providing a source of electricity.

v. Pollution can degrade the efficiency of solar collectors and panels. Clouds also produce the same effect, as they can reduce the energy of the sun's rays. Although, recent technologies have in-built components to overcome the worst of these effects.

vi. The location of solar collectors or panels can affect performance, due to possible obstructions from the surrounding buildings or landscape.

vii. Social ethics and consequences might also make it susceptible to being a distant reality.

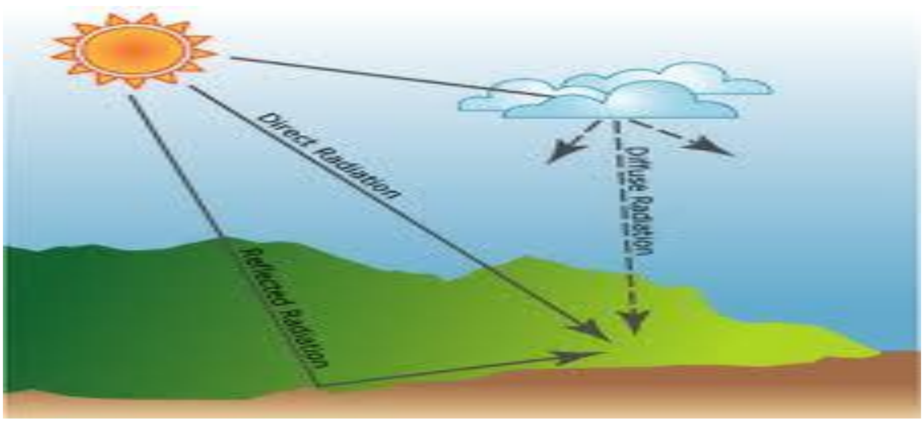

Figure 5 Factors affecting solar radiation. Source: ESRI[4]

[4] Solar radiation images.

CHAPTER TWO

2.1 LITERATURE REVIEW

2.1.1 Overview

The goal of this research has been defined in chapter one, but gathering earlier conducted related researches was not as easy as it was anticipated. Many research scholars had worked on this interesting technology but very few discussed issues related to my intended aim. Therefore, thorough pre-requisite knowledge of "Numerical Heat Transfer", Mass transfer, turbo-machinery and technical thermodynamics I have gathered were put into use. However, I was able to read through a number of research resources about the project, all of which can be seen below;

- Solar chimney technology (http://en.wikipedia.org/wiki/Solar_chimney): This link provided the basic history and explained explicitly the technology behind the solar updraft tower.

  One of the earliest descriptions of a solar chimney power station was written in 1931 by a German author, Hanns Gunther.

- More recently Schlaigh, Bergerman and Partners, http://www.sbp.de under the direction of German engineer Prof. Dr.-Ing. Joorg Schlaich built a working model of a solar chimney power plant in 1982 in Manzanares (Spain), 150 km south of Madrid, which was funded by the German Government. This power plant operated successfully for approximately 8 years. The chimney had a diameter of 10 m and a height of 195 m, and the maximum power output was about 50 KW. During the final 3 years, optimization data was collected on a second-by-second basis.

- http://www.greentower.net/UNIVERSITY%20STUDY.htm: A detailed report from the University of Stellenbosch from 2000, discussing a solar chimney in South Africa, and provided useful and interesting figures.

- http://www.scaf.ch : A website explaining the principle of small-scale solar towers called SCAF (Solar City Air Filters), which are designed to produce energy, but also to recycle polluted city air. It also envisaged the Bernoulli continuity equation.
- www.floatingsolarchimney.gr : This link provided a short and concise presentation on a floating type of solar tower and argued that the technology is by no way, a perpetual machine of any kind, as it seemed.

  However, a number of findings have been carried out extensively on this robust and green technology, which is reviewed below;

The solar chimney power plant system, which consists of three primitive and proven technological components, collector, chimney, turbine and energy storage layer, was first proposed in the late 1970s by Professor Joorg Schlaich and tested with a prototype model in Manzanares, Spain, in the early 1980s [P.15].

In the recent years, more and more researchers have shown strong interest in studying such solar thermal power generating technology for its huge potential of application all over the world. [P.15]

Four pilot solar chimney power models were in succession built by Krisst, Kulunk, Pasurmarthi and Sheriff, Zhou et al. The researchers also carried out experimental investigations on the performances of the models [P.15].

More theoretical investigation and simulations have been carried out by Padki and Sheriff, Lodhi , Bernardes et al. , von Backström and Gannon , Gannon and von Backström, Pastohr et al. , Schlaich et al. , Bilgen and Rheault , Pretorius and Kröger , Ninic, Onyango and Ochieng [P.15].

Haaf et al. provided fundamental studies for the Spanish prototype in which the energy balance, design criteria and cost analysis were discussed and reported preliminary test results of the solar chimney power plant [P.15, P.36].

Bernardes et al. developed a comprehensive thermal and technical analysis to estimate the power output and examine the effect of various ambient conditions and structural dimensions on the power output [P.15, P.37].

Pastohr et al. carried out a numerical simulation to improve the description of the operation mode and efficiency by coupling all parts of the solar chimney power plant including the ground, collector, chimney, and turbine [P.15, P.38].

Schlaich et al. [P.15, P.39] presented theory, practical experience, and economy of solar chimney power plant to give a guide for the design of 200MW commercial solar chimney power plant systems.

Ming et al. [P.15, P.40] presented a thermodynamic analysis of the solar chimney power plant and advanced energy utilization degree to analyze the performance of the system, which can produce electricity day and night.

Liu et al. [P.15, P.41] carried out a numerical simulation for the MW-graded solar chimney power plant, presenting the influences of pressure drop across the turbine on the draft and the power output of the system.

The purpose of this survey is to provide a review of the past researches related to the current research done which are; solar collector, solar tower, wind turbine and the robust solar updraft tower.

2.1.2 Solar Collector

Solar collectors are types of non-concentrating collector whereby the area intercepting the solar irradiation is the same as the absorber area. Thus, these type of collector ensure that the whole solar panel absorbs the light. Simply put, a collector is typically a device used for converting or transforming energy in solar radiation into a more usable or storable form. The advantage of using a collector in the form of a greenhouse, is that, it exhibits a phenomenon called “the greenhouse effect” by allowing solar flux from sunlight into the membrane (collector, whether diffuse and or direct) but does not allow heat out of it.

The energy in sunlight is in the form of electromagnetic radiation (ranging from infrared to the ultraviolet wavelengths). It is pertinent to know that, the solar energy striking the Earth's surface depends upon the weather conditions, location and direction of the surface absorbing it.

Figure 6 Non-concentrating solar collector

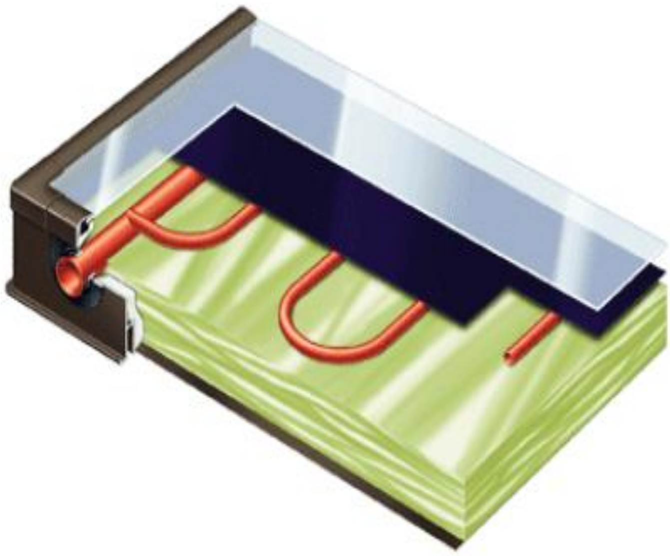

Figure 7 Components of a flat-plate collector. **Source: RRE**[5]

2.1.3 Solar Tower

The solar tower is the vertical shaft utilizing solar energy to enhance natural stack ventilation. It embodies the wind turbine which generates the energy in the form of electricity. This tower is designed in such a way that it obeys the concept of black-body radiation. It is to be perceived as a black-body whose emmissivity, transmissivity and absorptivity coefficients are unitary. This is so,

[5] Prof. Dr.-Ing Robert Pietzsch

in order that, it can absorb the sun's heat more easily and efficiently. Thus, its geodetical height, cross-section area and thermal properties are mostly relevant. The differences between the inlet and outlet air velocities and densities in the updraft tower is used to drive the wind turbine.

Figure 8 A typical solar tower. **Source: R.Spencer[6]**

2.1.4 Wind Turbine

A wind turbine is a device that converts kinetic energy from the wind into mechanical energy. Since the mechanical energy is used to produce electricity in the case of an updraft tower, the device may be called a wind generator or wind charger. The turbine can be a vertical axis or horizontal axis type. Both types have their merits and demerits, depending upon the desired speed and power output needed. However, it is not ideal to design a turbine that is vulnerable to wind turbulence and also produce higher torque. This may encourage dynamic loading and vibration,

[6] Solar-Towers.

such as noise and bearing wear which may increase its maintenance cost or shorten its service life. However, the choice of turbine used is a function of the intended output parameters.

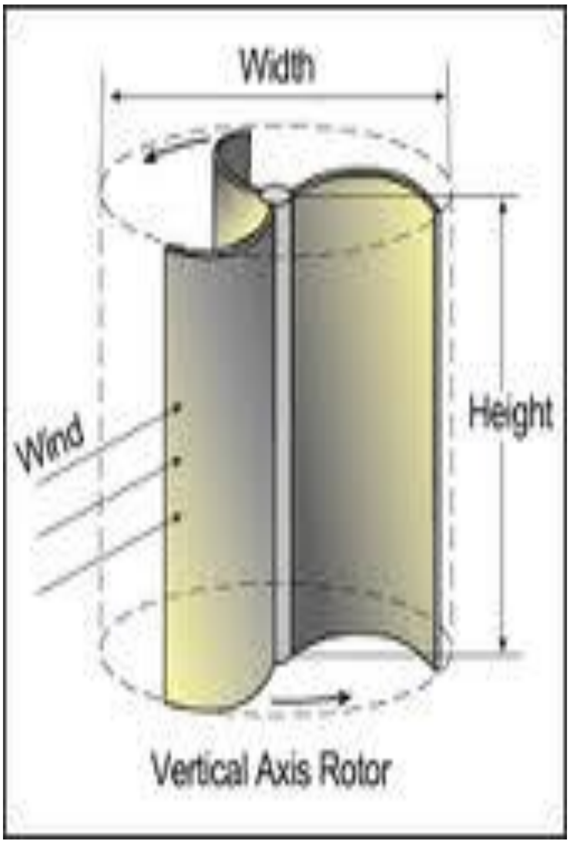

Figure 9 Figure 8 Vertical axis wind turbine.

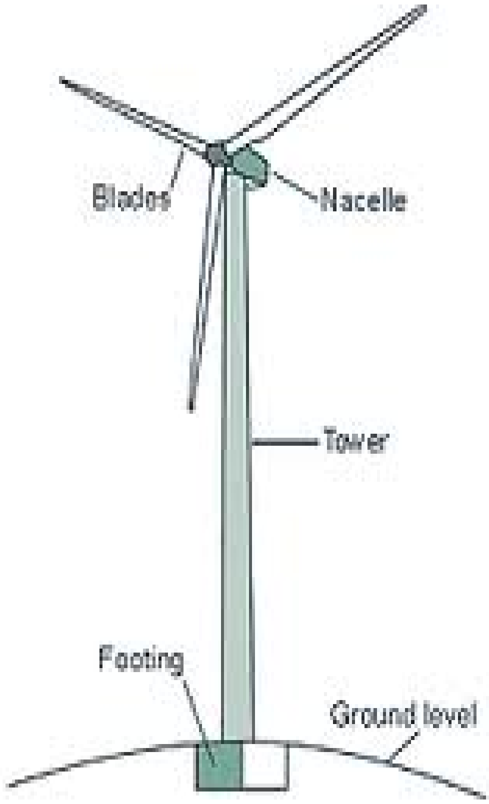

Figure 10 Figure 9 Horizontal axis wind turbine. Source: COL-ANT

CHAPTER THREE

3.1 RESEARCH METHODOLOGY

3.1.1 Introduction

It is evident that the energy from the sun reaching the earth drives the thermodynamic cycle in the solar collector set up. Consequently, the surface receiving the radiation is, in practice, perpendicular to the incident radiation which is thus, unsuitable for the efficiency of the solar collector. The solar irradiance can be measured by using the inverse square law and then converted to the desired horizontal irradiance.

3.1.2 Surface Irradiance of the Sun

The solar intensity emitting or radiating from the sun depends largely upon its peak wavelength, λ_{max} and temperature. In accordance with the "*Wien Displacement Law",* thus;

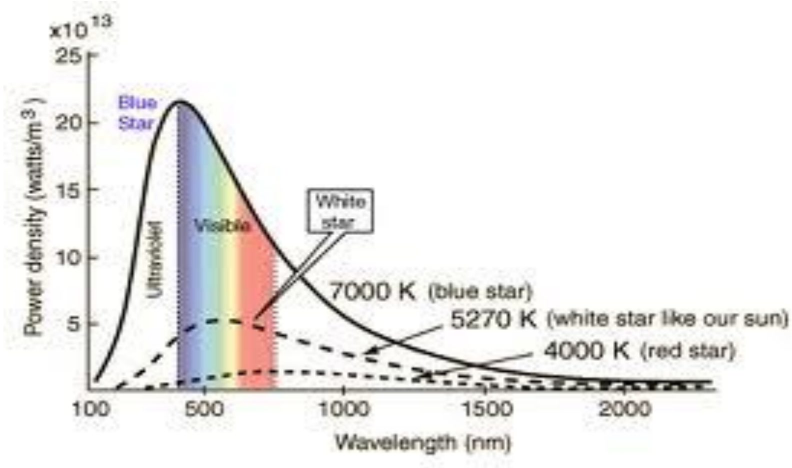

Figure 11 Wien Displacement law of electromagnetic wave propagation. Source: Hyperphysics[7]

$$\lambda_{max} = \frac{2897}{T} \tag{3.0}$$

Thence, the surface irradiance or radiation output, $\boldsymbol{E}$ of the sun can be evaluated using "*Stefan-Boltzmann Law"* when the temperature has been known from equation 3.0 above. Thus;

[7] hyperphysics.phy-astr.gsu.edu

$$\boldsymbol{E} = \epsilon\sigma T^4 \qquad (3.1)$$

Where;

$\boldsymbol{E}$ = Surface Irradiance of the Sun

ϵ = Emissivity of the Sun

σ = Stefan-Boltzmann Constant (5.67$\times 10^{-8}\ Wm^{-2}K^{-4}$)

T = Temperature of the Sun in Kelvin

It is however pertinent, to know that both Wien Displacement and Stefan-Boltzmann laws strictly apply to black bodies. Black bodies are capable of absorbing and emitting radiation at all wavelengths. But, since the Sun and Earth are not perfect black bodies, these laws only provide an approximation, hence certain correction factors like opacity, T_r transmitivity, τ, and absorptivity, α need to be taken into consideration.

3.1.3 Solar Radiation Entering the Solar Collector

Due to atmospheric effects such as cloud covers (opacity) and diffusion, not all the emitted energy from the sun reaches the solar collector. In fact, about 60% of the incoming radiation can be blocked by these effects. In accordance with the Inverse-Square law, the amount of energy reaching the collector can be determined if the surface irradiance of the sun derived in equation 3.1 above, is known. Thus;

$$\dot{I}^d = \frac{\boldsymbol{E} \times Surface\ area\ of\ the\ Sun}{Surface\ area\ of\ the\ collector}$$

$$\dot{I}^d = \boldsymbol{E} \times \frac{4\pi R^2}{4\pi r^2} \qquad (3.2)$$

Therefore, to estimate the solar constant, S_c which results from the effect of direct radiation in the absence of reflective and diffusive effects, equation 3.2 can be simplified, thus

$$S_c = \boldsymbol{E} \times (R/r)^2 \quad (3.3)$$

Where;

R = Radius of the Sun (6.96 x 10^5 km)

r = Average Sun-Collector distance (1.5 x 10^8 km)

The solar constant, S_c (whose numeric value is 1368 Wm^{-2}) is an important value since it provides additional data in determining the surface Insolation, $\dot{I}_h$. This surface insolation is usually inaccessible even with the aid of satellites. The solar constant is conceptually thought of as the direct surface irradiance in the absence of atmospheric opacity, but of course, there is no atmosphere without impurities. The impurities are inherent as a result of human influence on the environment. Thus, this value depicts the maximum global irradiance the earth can receive and serves as a theoretical limit through which the surface insolation can be compared.

3.1.4 Insolation: Solar Radiation Striking the Horizontal Surface

There are a few inherent short comings when trying to relate the solar constant or direct radiation intensity calculation to its effect on the Earth's surface or solar insolation, thus;

- The calculation is computed for the top of the atmosphere and not for the surface of the Earth.
- The calculation assumes that the surface receiving the radiation (solar collector) is normal to the radiation.
- It assumes that the surface receiving the radiation is at a mean Sun-Earth distance.

- It also assumes that radiation emission from the Sun is constant, without taken into consideration, the diffused lights and cloud cover.

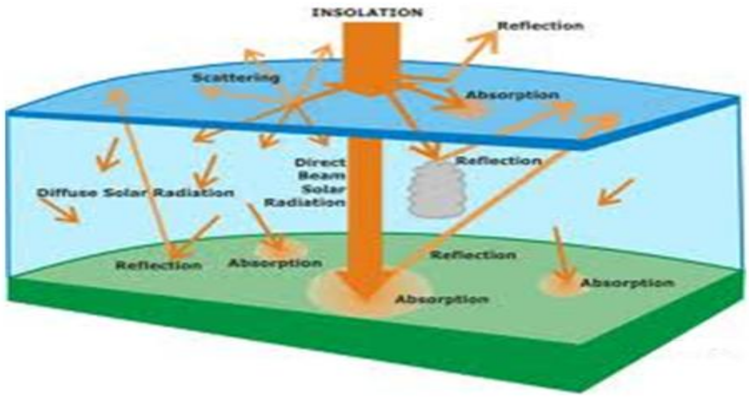

Figure 12 Surface Insolation. Source: UWSP[8]

And, the conversion of the direct solar irradiance at a given place to a horizontal area (insolation) can be interpreted from the below sketch, thus;

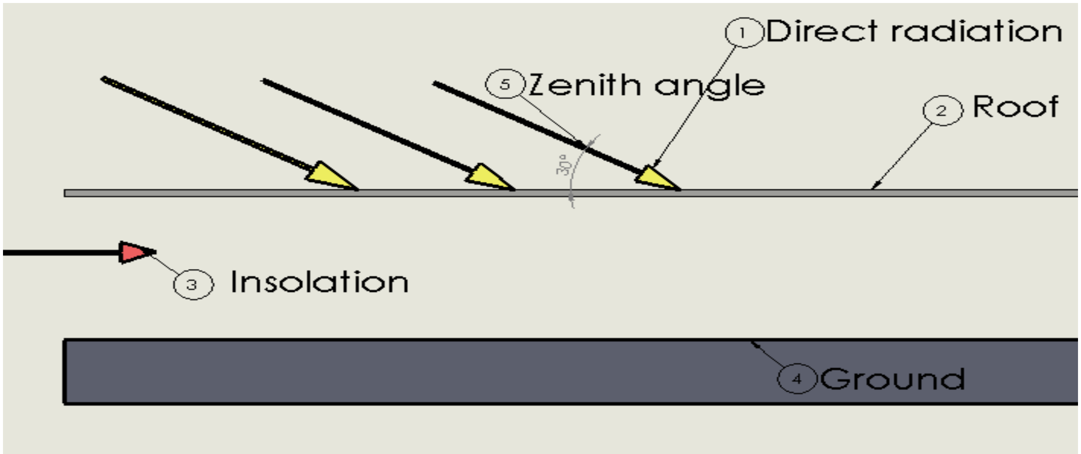

Figure 13 Analogy between direct radiation and Insolation.

Where $\dot{I}^d \stackrel{\text{def}}{=} S_c$ = 1368 Wm^{-2} in a situation where the weather is perfectly clear.

$\dot{I}_h$ = Surface Insolation (Horizontal global radiation intensity)

ψ = Zenith angle (Angle of incidence between, $\dot{I}_h$ *and* $\dot{I}^d$)

Where, the Zenith angle depends upon latitude, solar declination angle and time of the day.

[8] Uwsp.edu

$$\psi = \cos^{-1}(\sin\phi \sin\varphi - \cos\phi \cos\varphi \cos\beta) \quad (3.4)$$

3.1.5 Radiation Optimization of the Solar Collector

It therefore, follows that, in order to calculate the surface insolation, a set of parameters regarding the zenith angle, ψ (angle of incidence) and solar irradiation must be ascertained. And, it is important to estimate the global radiation striking the horizontal roof of the solar collector. This value depends upon several factors which include, thus;

i. Geometrical Orientation of the collector, N_s
ii. Opacity of the atmosphere, T_r
iii. Reflectivity, also known as albedo, σ
iv. Time angle, $\phi°$
v. Season (Time of the year), T_n
vi. Geometric position of the collector or Latitude
vii. Time of the day, t

However, V, VI and VII are commonly associated with a property called, the time reduction factor, μ_t.

Thence, the geometric reduction factor N_s can be expressed in relation to the inner angle of inclination of the collector as given below;

$$N_s = -\cos\varphi \cos\beta \cos\phi + \sin\varphi \sin\beta \quad (3.5)$$

β = Latitude,

φ = Solar declination angle,

$$\phi = \text{Time angle} = 15^0 \times (Time - 12) \quad (3.6a)$$

Equation (4.6a) can be re-written in a different form, as shown below;

$$\phi = \frac{t}{24hrs} \times 360° \quad (3.6b)$$

The solar declination angle, φ or inclination of the sun, can be expressed as a function of the season (time of the year) under consideration, thus;

$$\varphi = 23{,}5° \sin\left[\frac{360°}{365days}(T_n - 80days)\right] \quad (3.7)$$

And, the time-reduction-factor, $\mu_t$which often results from the atmospheric cloudiness, must be taken into account and can be expressed as;

$$\mu_t = \sin\left[180°.\left[\frac{t - S_r}{S_s - S_r}\right]\right] \quad (3.8)$$

Where;

$S_r\ and\ S_s$, are the sunrise and sunset times respectively.

$$S_r = \frac{12}{180°}\cos^{-1}(\tan\varphi \tan\beta) \quad (3.9)$$

It therefore, follows that, in the absence of reflective radiation, the global horizontal radiation (commonly called surface insolation) that would provide heat energy to the wind beneath the solar collector can be expressed thus;

$$\dot{I}_h = \mu_t.(N_s.\dot{I}^d + \dot{D}^{\circ}) \quad (3.10)$$

Where;

$\dot{I}^d$, is the direct radiation intensity, given by;

$$\dot{I}^d = 1300 - 120T_r \quad (3.11)$$

And, $\dot{D}^{\circ}$ is the diffuse radiation intensity, given by;

$$\dot{D}^{\circ} = 68 + 23T_r \quad (3.12)$$

For specific consideration of the educational model,

T (hour)	α°	N_s (%)	μ_t	$\mu_t \dot{I}^d$	$\mu_t \dot{I}_h$	$\dot{G}(W/m^2)$
10:00	150	0.82	0.927	760.55	148.40	908.95
11:00	165	0.91	0.981	804.99	157.07	959.18
12:00	180	0.94	1.000	820	160.00	980.00

Table 1 A table depicting the solar irradiance parameters.

3.2 Thermo-Fluid of the System

The robust solar updraft tower can be thought of as a control volume, whereby mass and energy are allowed to flow across its boundary. Thus, according to the 1st law of thermodynamics, the total rate of flow of mass and energy entering and leaving the system is conserved. In order to best analyze the thermo-fluid processes in the whole system, it is pertinent and intuitive to consider the turbine with it shaft and generator as a unique and separate entity.

3.2.1 Flow Mechanics of the Turbine Unit

One of the major design problem is how and where to position the wind turbine inside the tower, in order to fully utilize its functionability to produce the maximum possible power. Based on thorough understanding of fluid mechanics, the appropriate positioning of the turbine and a well manipulated dimensioning of the tower region would enable it work at its best.

3.2.1.1Energy Balance Equation

The figure below depicts a cut section of the chimney enveloping the axial wind turbine (vertical axis), with the inlet and outlet velocities. Although, both horizontal and vertical axis turbine type could be used to trap the wind energy and the thrust of force analysis would be different in each case, since the wind strikes the turbine blades in parallel and perpendicular direction respectively. The axial thrust is the rate of loss of momentum of the moving fluid.

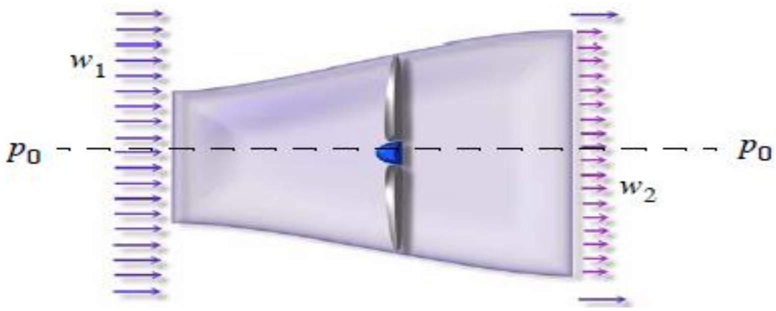

Figure 14 Wind flow across an axial wind turbine. Source: RRE note[9]

In a steady flow process, the wind upstream across the turbine, with the cross-section area A_1 and velocity w_1 possesses kinetic energy flowing per unit time, given thus;

$$K\dot{E} = \dot{P}_0 = ½\dot{m}w_1^2 \tag{3.13}$$

And the fluid mass flow $\dot{m}$ can be expressed in terms of the inlet air density and vapour specific volume $\dot{v}$. The latter being a function of the fluids cross-section and velocity, thus;

$$\dot{m} = \rho\dot{v} \tag{3.14}$$

And, $\dot{v} = A_1.w_1$

Therefore,

$$\dot{m} = \rho A_1.w_1 \tag{3.15}$$

Putting equation (3.14) into (3.12) yields;

[9] Prof. Dr.-Ing. Robert Pietzsch Renewable Resources Lecture Note.

$\dot{P}_0 = ½\ (\rho A_1 . w_1) w_1^2$

$$\dot{P}_0 = ½\rho A_1 w_1^3 \qquad (3.16)$$

It should be noted that, the air density ρ and velocity w_1 are the unperturbed state intensive properties at the inlet. And, equation (3.16) depicts the power in the wind at the said states. But, according to Sir Albert Betz's propounded theory; the maximum power the turbine can extract from this flowing wind would be a fraction of the total amount of power exactly available in the wind, since it is not perpetual motion machine.

Thence, the actual power that can be extracted from the flowing fluid can then be evaluated if the energy balance of the fig. 13 is taking into consideration. It is conventional that the air flow cannot be altered or stopped completely unless the turbine has to stop whirling. It means that the air mass flow through the turbine must be greater than null. The turbine is constantly extracting energy from this moving fluid to produce power, whose magnitude is negative, since it is an output path function. Therefore, an optimization problem must be solved during the energetic approach. It is necessary to define the thermodynamic system by considering the control volume around the turbine unit. The general energy balance equation for ideal gas (air) flowing at steady state is given as;

$$\dot{m}\ \left(h_1 + gz_1 + \frac{w_1^2}{2}\right) + \dot{Q} = \dot{m}\ \left(h_2 + gz_2 + \frac{w_2^2}{2}\right) + \dot{W} \qquad (3.17)$$

It should be noted that, the enthalpy values, h_i has taken into account the effect of boundary work (flow energy) since it is a function of both internal energy δU and;

$$\delta h = \delta U + P\delta V \qquad (3.18)$$

And; $\dot{W} - \dot{Q} = -\dot{P}$

Since the turbine is producing shaft power to drive the coupled or decoupled generator. Now, re-arranging the RHS and LHS of equation (3.16), yields;

$$\dot{m}\ \left((h_2\ - h_1\ ) + g(z_2 - z_1\ ) + (\frac{w_2^2}{2} - \frac{w_1^2}{2})\right) = -\dot{P} \tag{3.19}$$

It is intuitive to realize that the turbine and the entire system is at ground level in the tower, which makes the potential energy effect zero and also, at the unperturbed state, it was concluded that the air velocity and density are higher than the values after the turbine has extracted energy from it, thereby the enthalpy effect is insignificant and can be ignored compared to the kinetic energy effect of the air. Thence, equation (3.18) reduces to;

$$\dot{m}\ \left(\frac{w_2^2}{2} - \frac{w_1^2}{2}\right) = -\dot{P} \tag{3.20}$$

In order to estimate the mass flow, the velocity of flow must be the average of the inlet and outlet velocities, thus;

$$w_{avg} = \frac{w_1 + w_2}{2}$$

$$\dot{m}\ = \rho.\left(\frac{w_1+w_2}{2}\right).(\frac{\pi}{4}D^2) \tag{3.21}$$

Putting (3.20) into (3.19) yields;

$$\dot{P}\ = -\frac{\rho}{2}(w_2^2 - w_1^2).\frac{(w_1+w_2)}{2}.(\frac{\pi}{4}D^2) \tag{3.22}$$

Expanding equation (3.21) and factorizing as appropriate, yields an expression of power as a function of the cube of wind velocity, thus;

$$\dot{P}\ = \frac{\rho}{16}\pi D^2(w_1^3 + w_1^2 w_2 - w_1 w_2^2 - w_2^3)$$

$$\dot{P} = \frac{\rho}{16}\pi D^2 w_1^3(1 + x - x^2 - x^3) \quad (3.23)$$

From which, $x = w_2/w_1$ denotes the turbine tip-velocity ratio, hence a dimensionless factor whose value is needed to design the turbine to withstand dynamic loading.

It is technical to evaluate the optimum design characteristics of the wind turbine, because the rotation of the blades must be in such a way that, they are not whirling too slow or too fast, as the consequence is likely to produce a power deficiency. Thus, the wind flowing must all strike the moving blade in a sequential order so that the power extracted to drive the generator is as high as possible. In order to achieve this, equation (3.22) must be differentiated with respect to the tip-velocity ratio, and hence, the point of inflexion evaluated, thus;

$$\frac{\partial \dot{P}}{\partial x} = 1 - 2x - 3x^2 = 0$$

$x = -1$ *or* 1/3.

Since -1 is not admissible for wind velocity, it can be ignored, thus the appropriate value for x is $1/3$. It follows that, the optimum ratio between the inlet and outlet velocities of the wind striking the turbine blades is $1 : 3$.

i.e. $w_1 = 3w_2$ (*)

Thence, the maximum power inherent in this flowing wind, that the turbine can produce is gotten by replacing the numeric value of x in equation (3.22), and it's given by;

$$\dot{P} = \frac{2\pi}{27}\rho D^2 w_1^3 \quad (3.24)$$

From which a factor that compares the ratio of the optimum performance of the turbine to the performance of air flow with speed, w_1 can be derived, thus;

Power coefficient = equation (3.24): equation (3.16)

$$\varepsilon = \frac{\dot{P}}{\dot{P}_0} = \frac{\frac{2\pi}{27}\rho D^2 w_1^3}{½\rho A_1 w_1^3}$$

$$\varepsilon = \frac{16}{27} = 0.593$$

This implies that, the maximum energy the turbine can extract from the total kinetic energy of the wind into mechanical power to drive the generator is more or less 59%. It should be noted that, the power coefficient $\varepsilon,$ should not be confused with the turbine's efficiency.

3.2.1.2 Impulse Balance Equation

In designing the turbine unit to produce its maximum possible mechanical power, it is intuitive to evaluate the peripheral velocity, U of its blades or wheel and establish a relationship between it and the inlet velocity of the wind. This velocity bears an important relationship to the rotational speed, ω and has effect on the thrust exerted on the blades by the wind flow. Thus;

$$U = \omega.\frac{D}{2} \tag{3.25}$$

And,$\omega = \frac{2\pi N}{60}$ (3.26)

Where N is the rotational speed of the turbine wheel, measured inrad/s.

Replacing equation (3.26) into equation (3.25), yields;

$$U = \frac{2\pi N}{60}.\frac{D}{2}$$

$$U = \frac{\pi D N}{60} \tag{3.27}$$

Thence, the axial thrust exerted on the blades by the wind causes an impulse, whose magnitude can be determined by;

$$F_t = \dot{m}(w_1 - U) \tag{3.28}$$

Consequently, the power produced by the turbine due to the wind's impulsive force, can be expressed as;

$$\dot{P} = F_t . U \tag{3.29}$$

Re-arranging and substituting (3.27) accordingly into (3.28) yields;

$$\dot{P} = \dot{m}(w_1 - U). U \tag{3.30}$$

It thus, follows that, the power produced by the turbine due to impulsive thrust of the wind on the blades must have the same effect in magnitude, as that produced due to the kinetic energy the wind exert on the blades. That is, equation (3.29) and (3.19) must be equal. Therefore, we can evaluate the relationship between the wind speed and the turbine's peripheral speed.

$$\dot{m}\,\left(\frac{w_2^2}{2} - \frac{w_1^2}{2}\right) = -\dot{P} = -\dot{m}(w_1 - U). U$$

$$\Rightarrow \left(\frac{w_1^2}{2} - \frac{w_2^2}{2}\right) = -\dot{m}(w_1 - U). U$$

From the behaviour and set up of the turbine unit, it is obvious that $w_2 = 0$ and $w_1 = w - U$; this is because, the wind velocity would tend to overcome the opposing peripheral speed of the turbine. Thence, the analysis simplifies to;

$$\Rightarrow \frac{(w-u)^2}{2} = -(w - u)u$$

$$\Rightarrow ½w^2 - wu + ½u^2 = -wu + u^2$$

$\Rightarrow ½w^2 - ½u^2 = 0$

$\Rightarrow w = u$

The above relation between the wind's inlet velocity and the turbine's peripheral velocity depicts that, the maximum speed the turbine blades can attain bears a direct proportion to the wind's speed. But, the maximum power delivered by the turbine would be at the peak of the characteristics curve of $\dot{P} - u$ as shown below. This characteristic curve depicts the behaviour of the turbine blades peripheral speed relative to the output maximum power delivered by the turbine.

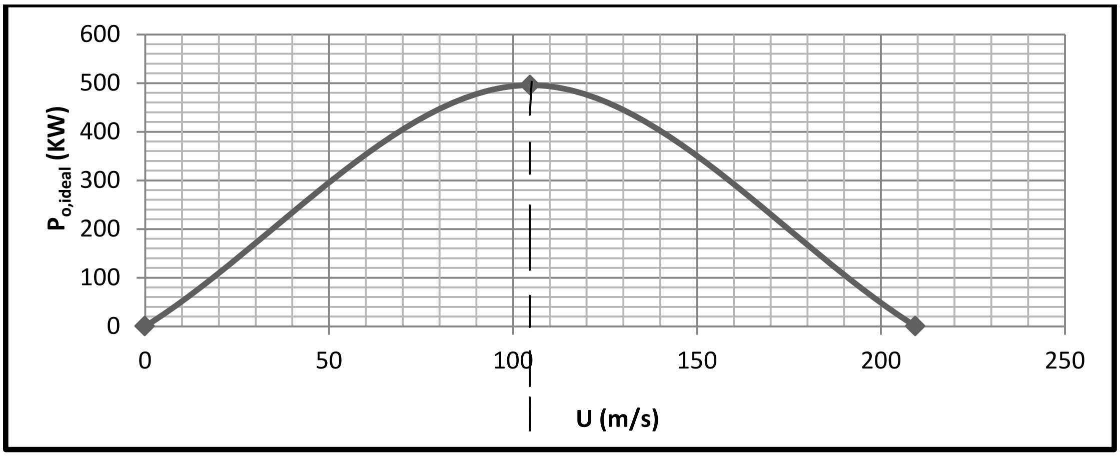

Figure 15 Characteristics curve of max. Power vs. peripheral speed.

It follows that, the maximum power the turbine can deliver, would be at the point where $u = {}^{w}/_{2}$, thus;

$$\dot{P}_{max} = \dot{m}\frac{w^2}{4} \tag{3.31}$$

It is of course, important to relate the power-peripheral velocity in order to be able to study the effect the former would have on the latter, and compare with equation (3.30). This is possible, if the wind velocity is first evaluated with the theory postulated by Bernoulli, thus;

$$\frac{P}{\rho g} + \frac{w^2}{2g} + z = c \tag{3.32}$$

Equation (3.31) is commonly referred to as the pressure head, since each of the expression is dimensionally consistent and in the unit of head (height). If rearranged, yields;

$$P + \rho \frac{w^2}{2} + \rho g z = c \tag{3.33}$$

Since, the drop along the horizontal cross-section is infinitesimally small compared to other effects, thence, $P = 0$. And;

$$\rho \frac{w^2}{2} = \rho g z$$

Whence $w = \sqrt{2gz}$ (3.34)

This is the velocity sufficiently needed for the wind to rotate the turbine; whereas the turbine's peripheral velocity can be determined.

$$u = \sqrt{\frac{gz}{2}} \tag{3.35}$$

Now, expressing the maximum power offered by the turbine in terms of the peripheral velocity, yields;

$$\dot{P}_{max} = \dot{m} \frac{gz}{2} \tag{3.36}$$

3.2.1.3 Mass Balance Equation

The turbine unit can be thought of as being a control volume and the flow process assumed to be a steady-flow process. Then, viewing the turbine and the enclosed region as the system while the inside wall of figure 3.3 is the boundary. It is intuitive to model the unit in accordance with the 1st law of thermodynamics. Thus;

$$\frac{dm}{dt} = 0$$

$\Delta\dot{m} = \dot{m}_{out} - \dot{m}_{in}$

Thence,

$\dot{m}_{in} = \dot{m}_{out}$

$\Longrightarrow \dot{m}_1 = \dot{m}_2$

$$\dot{m}_1 = \frac{P_u}{R_s T}\dot{V} \tag{3.37}$$

Where;

P = the atmospheric pressure in Pa.

T = the ambient absolute temperature in Kelvin

$\dot{V}$ = the volumetric flow rate in m^3/s

R_s = the specific gas constant in J/KgK

$$R_s = \frac{R_u}{M_m} = 287\,J/KgK \tag{3.38}$$

Where;

R_u = the universal gas constant, 8314$J/Kmol$

M_m = the molar mass of air, 28.98Kg/mol

3.3 Design of the Turbine Unit

In order to extract the best possible power from the turbine, there should exist a unique relationship between the inlet and outlet diameters. This is true because, the mean free diameter of the air should be at least larger than the diameter of the turbine unit, so that, the perturbation or turbulence makes it possible for the air flow to loss as much of its energy as possible to the turbine. It follows that; the upper diameter of the tower should be larger than the lower end where the turbine is housed. This design would of course seem as a threat to the strength and stability of the tower, hence the need to compensate the design with appropriate material selection. Recall from the mass balance equation, that;

$$\dot{m}_1 = \dot{m}_2$$

$$\rho_u A_1 w_1 = \rho_o A_2 w_2$$

In the unperturbed state, $\rho_u = \rho_o$

$$A_1 w_1 = A_2 w_2$$

From (**) in preceding section, $w_1 = 3w_2$

$$A_1 . 3w_2 = A_2 w_2$$

$$3\left(\frac{\pi}{4}\right) d_1^2 = \left(\frac{\pi}{4}\right) d_2^2$$

$$d_2 = \sqrt{3}. d_1 \qquad (**)$$

Equation (**) above implies that, the best possible way to design the inlet diameter to the outlet diameter is in the ratio of $1{:}\sqrt{3}$. However, this design may pose mechanical threat upon the tower since adequate strength of materials and mechanics knowledge and input would be required.

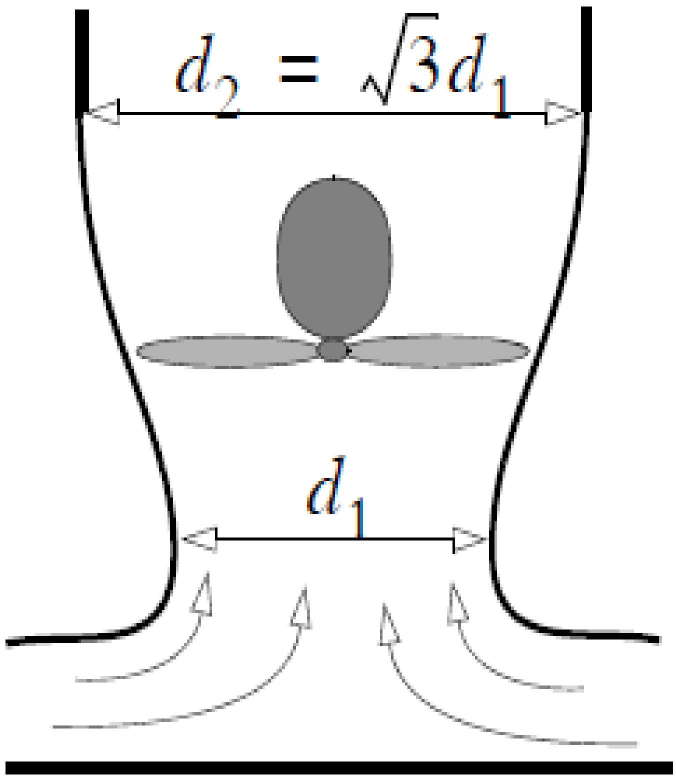

Figure 16 Schematic of the turbine unit. Source: RRE note

It should be emphasized at this juncture that, the design of the wind turbine shown in figure 15 above is in accordance with the fundamental principles of flow mechanics. Thus, applying this numerical computation in the fabrication of our turbine unit would in no way violate any known technical fundamentals.

As the air under the solar collector and heat exchanger warms up, it density becomes apparently lighter which leads to higher flow velocity. This is thus, the basis with which the plant executes its thermodynamic cycle. Since, the lighter air has many tendencies to displace the colder air above it, thence, creating a convective pool upward in the wind turbines direction. Therefore, the relationship between the inlet diameter and the diameter behind the turbine must be in the calculated ratio.

3.3.1 Thermodynamics of the Solar Updraft Tower

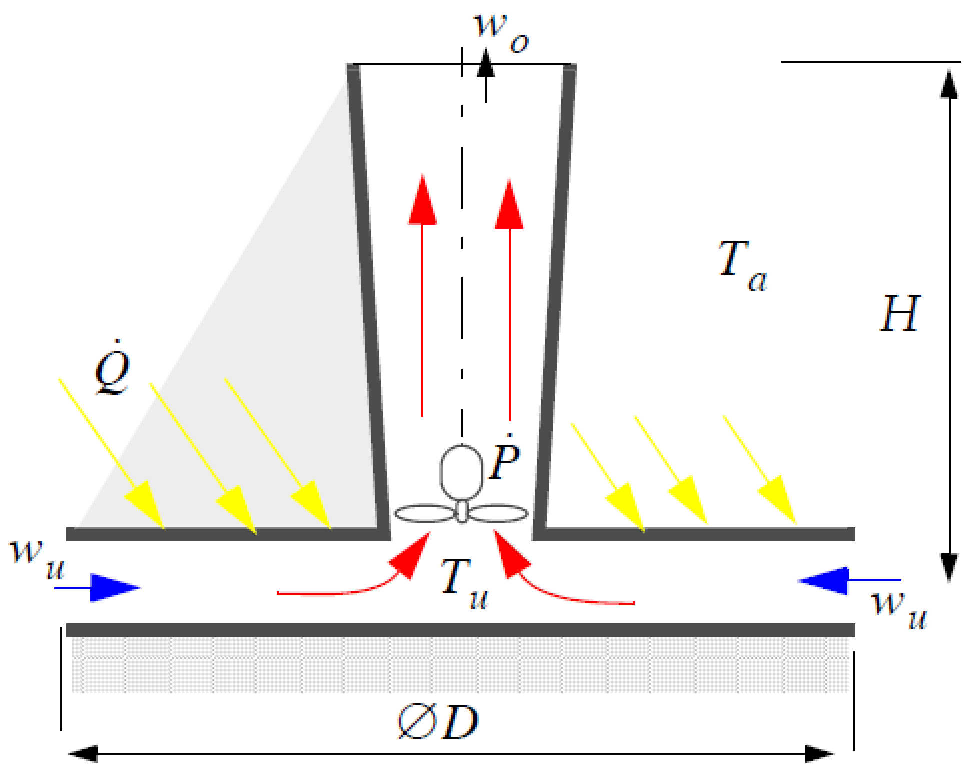

Figure 17 Thermo-Fluid of solar updraft Tower. Source: RRE note.

The above figure can be thought of as a control volume, thus obeying the first law of thermodynamics. This means, that mass or energy can neither be created or destroyed, although can be transformed from one form to the other. As the solar irradiance is converted into solar insolation, it warms up the entrapped air present in the greenhouse or air collector, which are then forced to generate convective heat flow, that are up-drafted to drive the turbine. It can be inferred that the sole purpose of the thermodynamic analysis of this tower is to evaluate the output power $\dot{P}$ as a function of the geometric parameters and the heat input $\dot{Q}$ generated from the solar irradiance.

3.3.2 Energy Balance (Radiation Optimization) of the Solar Collector

The solar collector can be viewed as an open system in its entity, therefore allowing mass and energy to flow across its boundary. The convective flow of air inside the collector is modelled as a quasi-static flow, and the energy balance can be formulated thus;

$$\dot{Q}_{in} = A_c . \dot{I}_h . \eta_{conc} \tag{3.39}$$

Whereas, from the concept of elementary heat transfer, it is evident that the heat flow (heat transfer) between two bodies of different temperatures is;

$$\dot{Q} = \dot{m}c_p\delta T \qquad (3.40)$$

Equating (3.39) and (3.40) yields;

$$\dot{Q} = A_c.\dot{I}_h.\eta_{conc} = \dot{m}c_p\delta T$$

$$\dot{Q} = \frac{\pi}{4}D^2\dot{I}_h\eta_{conc} = \dot{m}c_p(T_u - T_o) \qquad (3.41)$$

From which the hot source temperature can be computed, thus;

$$T_u = T_o + \left(\frac{\frac{\pi}{4}D^2\dot{I}_h\eta_{conc}}{\dot{m}c_p}\right) \qquad (3.42)$$

From the 1st law of thermodynamics;

$$H = U + PV$$

$$\dot{m}c_p\delta T = \dot{m}c_v\delta T + \dot{m}R_s\delta T$$

$$c_p = c_v + R_s$$

And from the theory of statistical thermodynamics, air can be thought of as a perfect gas whose degree of freedom ≈ 5. Thence;

$$c_v = \frac{5}{2}R_s$$

$$c_p = \frac{5}{2}R_s + R_s = \frac{7}{2}R_s \qquad (***)$$

Now, equation (3.41) can be re-written in a suitable form as;

$$\dot{Q} = \frac{\pi}{4} D^2 \dot{I}_h \eta_c = \dot{m} \frac{7}{2} R_s (T_u - T_a) \tag{3.43}$$

Where;

$\dot{I}_h = \mu_t . (N_s . \dot{I}^d + \dot{D}^\circ)$, is the solar intensity on the horizontal surface of the collector, calculated according to the principle of solar thermodynamics from equation (3.10).

T_u and T_a, are the absolute temperatures of the flowing air from the hot source and ambient respectively.

<u>3.3.3 Pressure Distribution inside the Collector and Tower</u>

The convective heating inside the solar collector takes place while the pressure of the air is kept constant i.e. isobaric process. And the states *o* and *u* can be related as follows;

$$\rho_u T_u = \frac{P_a}{R_s} = \rho_o T_o \tag{3.44}$$

And, from the theory of fluid mechanics, pressure decreases with altitude. This implies that, the pressure at the bottom of the tower P_a would be exponentially larger than that at the top of the tower P_o as shown below;

$$\frac{dP}{dz} = -K = \rho g$$

$$\frac{dP}{dz} = -\rho g$$

$$\frac{dP}{dz} = -\frac{P}{R_s T} g$$

$$\int_{P_u}^{P_o} \frac{dP}{P} = -\frac{g}{R_s T} \int_0^z dz$$

This resolves to;

$$P_o = P_u e^{-\frac{gz}{R_S T}} \quad (3.45)$$

For simplicity reason, let $B = e^{-\frac{gz}{R_S T}}$

So that,

$$P_o = P_u B$$

Where,

P_u = Atmospheric pressure at the base of the tower, 101325Pa

P_o = Pressure at the top of the tower, whose magnitude depends upon the relation (3.45).

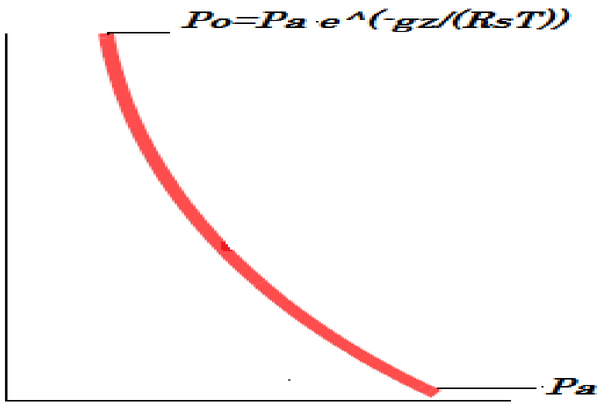

Figure 18 Pressure distributions curve along the Tower.

3.4 Energy Balance of the Tower

In analyzing the energy interactions inside the updraft tower, it is pertinent to know that both the theoretical (ideal or reversible) and the actual (real or irreversible) cases play an important role in the design of this green power plant, if maximizing the efficiency (i.e. extracting the maximum allowable power from the wind turbine) is the sole purpose. Thence, the two cases would be described analytically, thus;

3.4.1 Ideal Process (Reversible Adiabatic Process)

It is evident from the concept of engineering thermodynamics that, turbines exploits the energy inherent in the heat transfer fluid impinged on their rotating blades and thus produces power by driving a coupled or decoupled generator; hence, this power is a negative type since the system is doing work.

$$-\dot{P} = \dot{m}\left[(h_o - h_u) + \frac{1}{2}(w_o^2 - w_u^2) + gH\right] \tag{3.46}$$

Whereas, specific enthalpy is described for the heat transfer fluid by;

$$h = C_p T \qquad (****)$$

Substituting equation (***) into (****), yields;

$$h = \frac{7}{2} R_s T \tag{3.47}$$

The air flow velocity at the bottom of the tower w_u is smaller when compared with that at the upper outlet w_o, and to ensure that all the energy interactions within the tower is accounted for, the air flow has to be accelerated through it from zero to w_o. Accordingly, $w_u^2 \ll w_o^2$ and thus the term w_u^2 in equation (3.44) can be ignored, without significant error. Modifying the energy balance to suit the assumptions, yield;

$$-\dot{P} = \dot{m}\left[\frac{7}{2} R_s (T_o - T_u) + \frac{1}{2} w_o^2 + gH\right] \tag{3.48}$$

Ideally, there is no heat loss in this tower, therefore, the reversible adiabatic expansion of the heat transfer fluid between states o and u at the top and bottom respectively, can be expressed as follows;

$$\frac{T_o}{T_u} = \left(\frac{P_o}{P_u}\right)^{\gamma} = B^{\gamma} \tag{3.49}$$

$$\frac{\rho_o}{\rho_u} = \left(\frac{P_o}{P_u}\right)^{1-\gamma} = B^{(1-\gamma)} \tag{3.50}$$

Where,

$\gamma = \frac{k-1}{k}$, and K is the isentropic exponent with magnitude of $7/5$

Thence, the mass flow can be computed in terms of the newly defined variables as follows;

$$\dot{m} = \rho_o w_o A_o = \rho_u B^{(1-\gamma)} w_o A_o = \frac{P_u}{T_u R_s} B^{(1-\gamma)} w_o A_o \tag{3.51}$$

Consequently, the air velocity w_o at the top of the tower can be determined by;

$$w_o = \frac{R_s}{P_u B^{(1-\gamma)} A_o} \dot{m} T_u = C \dot{m} T_u \tag{3.52}$$

Where C is a constant, given by:

$$C = \frac{R_s}{P_u B^{(1-\gamma)} A_o} \tag{3.53}$$

Having derived expressions for the outlet velocity of flow and modelled the tower as a perfect black body, such that it is quasi-static and reversibly adiabatic, the energy balance equation becomes;

$$-\dot{P} = \dot{m}\left[\frac{7}{2} R_s T_u (B^{\gamma} - 1) + \frac{1}{2} C^2 T_u^2 \dot{m}^2 + gH\right] \tag{3.54}$$

This simplifies to;

$$\dot{P} = -\left[\frac{1}{2} C^2 T_u^2 \dot{m}^3 + (K T_u + gH)\dot{m}\right] \tag{3.55}$$

It is however, obvious that the performance of the power plant is dependent upon the third power of the heat transfer fluid mass flow, with;

$$K = \frac{7}{2} R_s (B^\gamma - 1) < 0 \quad (3.56)$$

The functional relationship equation (3.53) for the output power is a vital part of this analysis and it is imperative to illustrate the dependency of the power on the fluid mass flow whether analytically or graphically or both, as would be shown subsequently.

The performance peak of the robust design would exist at the point of inflexion of the output power. Thus, the mass flow is at its optimum at the point where the output power is maxima.

Differentiating equation (3.53) with respect to the mass flow yields;

$$\frac{\partial \dot{P}}{\partial \dot{m}} = 0 = \frac{\partial}{\partial \dot{m}} \left[\frac{1}{2} C^2 T_u^2 \dot{m}^3 + (KT_u + gH)\dot{m} \right] \quad (3.57)$$

$$\Rightarrow \frac{3}{2} C^2 T_u^2 \dot{m}^2 = -(KT_u + gH)$$

Thence, the optimum mass flow becomes;

$$\dot{m}_{opt} = \sqrt{-\frac{(KT_u + gH)}{\frac{3}{2} C^2 T_u^2}}$$

$$\dot{m}_{opt} = \frac{1}{CT_u} \sqrt{-\frac{2}{3}(KT_u + gH)} \quad (3.58)$$

Now, since it has been shown that the power output depends upon the third power of the mass flow, then;

$$\dot{P}_{max} \propto \dot{m}_{opt}^3$$

The maximum power output then becomes;

$$\dot{P}_{ideal,max} = \frac{1}{CT_u} \left[-\frac{2}{3}(KT_u + gH) \right]^{3/2} \quad (3.59)$$

The above expression is the maximum possible power output of the turbine in the reversibly adiabatic (ideal) process. The deceleration of the airflow to the optimal value must therefore be reassured by designing the turbine blades in the best possible way. It has been shown in section 3.6.2 that, the tower must be designed in such a way that the pipe around the turbine unit be three times wide as the upper cross-section, i.e. to $\sqrt{3}$ times the diameter so that the optimum tip-speed ratio does not contradicts the Albert Betz ratio;

$$w_x = 3w_o$$

3.4.2 Real Process (Irreversible Process)

The solar power plant under study is typically an irreversible plant, because the thermodynamic cycle cannot be concisely restored to its initial state no matter how infinitesimally small, the changes in some property of the system is, without trading off energy. It means that, energy losses between the system and its surrounding cannot be avoided, hence, must be accounted for in the energy balance equation. These energy losses can take different form, since energy is convertible even though it cannot be formed. The mostly inherent losses in the solar updraft tower are, flow friction, pressure losses and heat losses.

3.4.2.1 Friction Loss

It is evident that, real gases behave in such a practical way that, certain correction factors need be introduced into the general gas laws to account for their anomalous behaviour. In the irreversible process, the steady flow energy equation, SFEE must take into account, the effect of frictional losses inside the wall of the tower, since there has been no perfectly designed cylindrical duct whether metallic or plastic. In order to account for the frictional loss in this design, the SFEE can be re-computed thus;

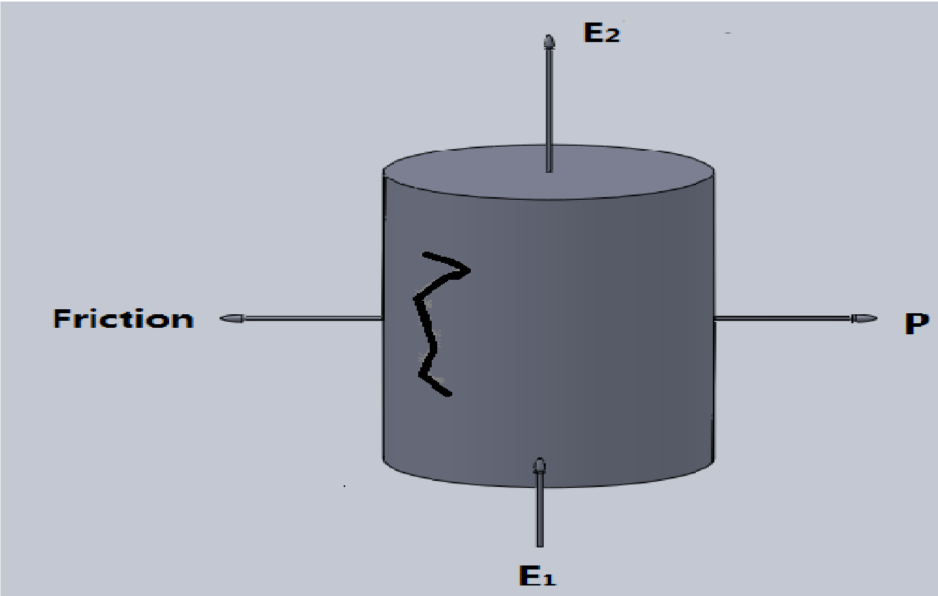

Figure 19 Energy balance diagram for real case.

$$\dot{m}\,\left(h_u + gz_1 + \frac{w_u^2}{2}\right) = \dot{m}\,\left(h_o + gz_2 + \frac{w_o^2}{2}\right) + h_f + \dot{P} \tag{3.60}$$

As claimed earlier the inlet potential energy and kinetic energy effects are negligible compared to the inlet enthalpy, therefore, they can be discarded to yield;

$$-\dot{P} = \dot{m}\left[\frac{7}{2}R_s(T_o - T_u) + \frac{1}{2}w_o^2 + gH + \xi\,\frac{w_o^2}{2}\right] \tag{3.61}$$

From which;

$$h_f = \xi\dot{m}\,\frac{w_o^2}{2} \tag{3.62}$$

Where;

h_f= the head loss due to friction, measured in J/s and

ξ = the roughness coefficient, a dimensionless factor.

Now, the actual power output of the turbine, becomes;

$$\dot{P}_{actual,max} = \frac{1}{CT_u}\left[-\frac{2}{3}\left(\frac{(KT_u+gH)}{(1+\xi)}\right)\right]^{3/2} \tag{3.63}$$

The presence of losses in this robust power plant explains why its efficiency can never reach the maximum theoretical limit, proposed by Sadi Carnot. The head loss due to frictional effects in the vertical tower must also be in the unit of power to ensure dimensional consistency.

3.4.2.2 Pressure Loss

It is evident that the hot air within the tower weighs less than that outside the tower. Then it can be concluded that there is a pressure drop along the tower, as the air rises. Since, pressure decreases with altitude. Based upon a simple yet proven hydrostatic model, the air is in continues inward motion up the tower. The pressure drop due to gravitational effect only can be expressed as a function of the density difference, thus;

$$\Delta P = \int_0^H (\rho_u - \rho_o)\, g\delta H \qquad (3.64)$$

As a result of the elbow and tapered section of the tower, the pressure drop can be determined with the roughness coefficient computed from the Daisy-Weisberg equation. Therefore, the loss can be expressed in the form;

$$\Delta P = \xi \rho_o \frac{\overline{w}_o^2}{2} \qquad (3.65)$$

Where; $\xi = \lambda . \frac{H}{d}$ (3.66a)

$$\overline{w}_o = \frac{w_u + w_o}{2} \qquad (3.66b)$$

And, λ is the friction co-efficient computed according to Blausius equation for turbulent flow;

$$\lambda = \frac{0.3164}{Re^{0.25}} \qquad (3.66c)$$

3.4.2.3 Heat Loss

Although, there are radiation and convective losses in the design of the power plant, but the latter effect does not produce alarming error in optimization, for the temperature range considered. It follows that, the radiation losses only is necessary to account for. Thence, this loss can be manipulated according to the Stefan-Boltzmann equation;

$$\dot{Q}_{lost} = A_c \epsilon \sigma T_u^4 \qquad (3.67)$$

Where;

A_c = the collector cross-section area in m^2

ϵ = Emissivity of the collector, which can be approximated to unity, for simplicity.

3.5 Carnot Efficiency and Overall Efficiency

The Carnot efficiency depicts the maximum theoretical efficiency that can be attained by the design and its magnitude depends largely upon the degree of entropy increase of the entire system. So, the design would work at its best if the temperature difference between the ambient and the temperature offered by the solar radiation is large enough.

3.5.1 First-Law (Thermal) Efficiency

The Carnot efficiency is in clear terms, an upper limit for the thermodynamic efficiency of the solar tower. Therefore;

$$\eta_{carnot} = \eta_{th}$$

$$\eta_{carnot} = \frac{Heat\ output}{Heat\ input} = \frac{T_u - T_o}{T_u} = 1 - \frac{T_o}{T_u} \quad (3.68)$$

Similarly, the efficiency of the collector can be computed thus;

$$\eta_c = \frac{Heat\ absorbed - Heat\ lost}{Heat\ input\ from\ solar} \quad (3.69)$$

$$\eta_c = \frac{\dot{Q}_{absorbed} - \dot{Q}_{lost}}{\dot{Q}_{in}} = \frac{\alpha\dot{Q}_{in} - \dot{Q}_{lost}}{\dot{Q}_{in}} \quad (3.70)$$

Where;

α = the absorptivity of the solar collector, and can be approximated to unity, for simplicity.

Inserting the equations (3.38) and (3.64) into (3.67), yields;

$$\eta_c = \frac{A_c.\dot{I}_h.\eta_{conc} - A_c\epsilon\sigma T_u^4}{A_c.\dot{I}_h.\eta_{conc}} = 1 - \frac{\sigma T_u^4}{\dot{I}_h.\eta_{conc}} \quad (3.71)$$

And the turbine thermal efficiency takes the form;

$$\eta_T = \frac{\dot{P}_{output}}{\dot{Q}_{in}} = \frac{\frac{1}{CT_u}\left[-\frac{2}{3}\left(\frac{(KT_u+gH)}{(1+\xi)}\right)\right]^{3/2}}{\dot{m}\frac{7}{2}R_s(T_u-T_o)} \tag{3.72}$$

Therefore the overall efficiency of the plant can be computed, thus;

$$\eta_{max} = \eta_{carnot}.\eta_c \tag{3.73}$$

From which;

$$\eta_{max} = \left(1 - \frac{T_o}{T_u}\right).\left(1 - \frac{\sigma T_u^4}{I_h.\eta_{conc}}\right) \tag{3.74}$$

The above expression depicts the overall efficiency that can be achieved from the thermodynamic cycle undergone by the plant. It can be seen that, the induced flow caused by stack effect (updraft) must be large enough to generate disorderliness within the air molecules. Since, it has been established from the Carnot efficiency expression that, high temperature gradient between the inlet (hot source or hotter temperature beneath the collector) and the environment temperature must be ensured, to attain the maximum theoretical efficiency possible.

3.5.2 Second-Law Efficiency

It is of utmost importance, to seek the best performance level of the wind turbine relative to the first best possible performance. This means that, evaluating the thermal efficiency alone is not enough, since the sole purpose of this robust design is to take advantage of the best output power. It follows that equation (3.72) has to be compared to the ideal performance efficiency. Only then, can it be plausible to estimate how much energy it can deliver. Therefore,

$$\eta_{II} = \frac{\dot{P}_{actual}}{\dot{P}_{ideal}} \tag{3.75}$$

This would simplify to;

$$\eta_{II} = \frac{\left[-\frac{2}{3}\left(\frac{(KT_u+gH)}{(1+\xi)}\right)\right]^{3/2}}{\left[-\frac{2}{3}(KT_u+gH)\right]^{3/2}} \tag{3.76}$$

Equation (3.76) above is the exergy or maximum work potential the wind turbine can produce under the specified conditions. The dead-state is the atmospheric conditions for both actual and ideal processes.

3.6 Humification Effect on Heating Zone

From the schematic of the heating-humidification process shown below in figure 19. The effect of air humidity on the heating zone inside the solar updraft tower can be analyzed, thus;

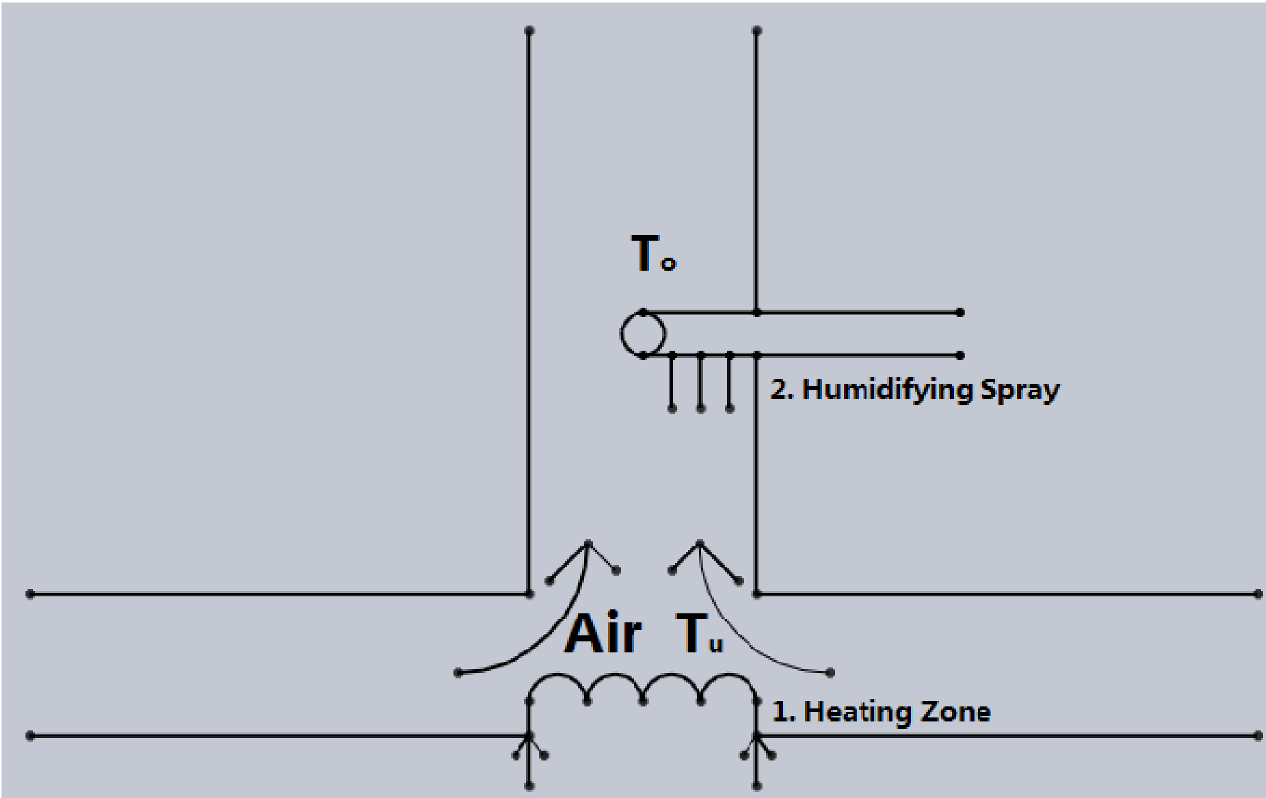

Figure 20 Effect of humidifying dry air.

Apart from the power-producing task expected from the solar updraft tower, human comfort as well as environmental friendly warm air must be ensured. However, humidifying the dry air inside the tower tend to serve a dual purpose;

1. To aid buoyancy of the air around the heating zone, thereby enhancing turbulence sufficient enough to drive the turbine.
2. To ensure that the air flow outward of the tower is humid.

Meanwhile, humidifying the air would result in temperature decrease with an overall effect on the efficiency output. Therefore, to correct this humidification-cooling effect, overheating of the dry air must be ensured before it accelerated to the humidifying zone. This process requires a lot more solar radiation than the estimated magnitude, because additional supply of heat does not affect the output performance of the turbine instead it only compensate for the temperature decrease due to humidity. Another important situation to be considered herein is how the humidification process is accomplished. Thus, if steam is introduced into the humidification zone, this will result into humidification with additional heating as earlier discussed. But if humidification is accomplished by spraying water into the dry airstream as depicted in figure 19 above, part of the latent heat of vaporization comes from the air which results in the cooling of the heated airstream.

The mass balance as well as energy balance of the heating-humidification process of the tower then becomes;

Mass balance of dry air;

$$\dot{m}_1 = \dot{m}_2 = \dot{m}$$

Mass balance of the moist air;

$$\dot{m}_1\omega_1 + \dot{m}_w = \dot{m}_2\omega_2 \quad (3.77)$$

Which yields;

$$\dot{m}_w = \dot{m}(\omega_2 - \omega_1) \quad (3.78)$$

Energy balance for the entire process;

$$\dot{m}\ \left(h_u + gz_1 + \frac{w_u^2}{2}\right) = \dot{m}\ \left(h_o + gz_2 + \frac{w_o^2}{2}\right) + \dot{P}$$

Where;

$$h_u = \frac{7}{2}R_sT_u + \omega_1 h_{g1} \quad (3.79a)$$

$$h_o = \frac{7}{2}R_sT_o + \omega_2 h_{g2} \quad (3.79b)$$

And;

$$\omega = 0.622\left(\frac{P_v}{P-P_v}\right) = 0.622\left(\frac{\emptyset P_g}{P-\emptyset P_g}\right) \quad (3.80)$$

$$\dot{P}_\omega = \dot{m}\left[\frac{7}{2}R_s(T_o - T_u) + (\omega_1 h_{g1} - \omega_2 h_{g2}) + \frac{1}{2}w_o^2 + gH\right] \quad (3.81)$$

All parameters with their usual meaning, thus;

P_v is the partial vapour pressure of the water vapour in Pa.

P_g is the saturated liquid pressure at the corresponding temperature in Pa.

h_g is the enthalpy of saturated water vapour at the given temperature per unit mass of dry air.

ω is the specific or absolute humidity of the dry air-water vapour mixture in %.

$\emptyset$ is the relative humidity of the water vapour content in %.

$\dot{P}_\omega$ is the output power due to humidification effect in KW.

3.7 Research Design

The analytical method of research was used for this study. To define the analytical type of research, Thesaurus (2003) stated that the analytical method of research is to gather information about the present existing condition and analyse it substantially by either experimental or basic approach. The emphasis is on analysing rather than on judging or interpreting. The aim of analytical research is to verify formulated hypotheses that refer to the present situation in order to elucidate it. The analytical approach is quick and practical in terms of the cost-time aspect. Moreover, this method allows a flexible approach, thus, when important new issues and questions arise during the duration of the study, further investigation may be conducted.

Analytical research on the other hand is a type of research that is mainly concerned with analysing the nature or condition and the degree in detail of the present situation. This method is used to describe the nature of a situation, as it exists at the time of the study and to explore the cause(s) of a particular phenomenon. The aim of analytical research is to obtain an accurate profile of the working sequence of the device and or different known designs. With this research type, it is essential that we already had a clear view or picture of the phenomena being investigated before the data collection procedure is carried out. However, we used this kind of research to obtain first hand data from the experiment so as to formulate rational and sound conclusions and recommendations for the study. The analytical approach is quick and practical in terms of the cost-time function.

In this study, the analytical research method was employed so as to identify the role and significance of using the fundamentals of engineering thermodynamics principles in evaluating and analysing the performance of the solar updraft tower during the time of research. We opted to use this research method considering the objective to obtain first hand data from the experimental measurement and modelling. The analytical method is advantageous due to its flexibility; this method can use either qualitative or quantitative data or both, giving room for greater options in selecting the instrument for data acquisition. The aim of the research is to design and analyze the thermodynamics of the solar updraft tower; the analytical method is then appropriate for this research since this method is used for gathering prevailing conditions.

The research is using experimental method and computational fluid dynamics analysis in order to gather relevant data; the analytical method is then appropriate as this can allow the identification of the behavioural pattern of the heat transfer fluid. For this research, two types of data were gathered. These included the primary and secondary data types. The primary data were derived from the experimental model designed in the laboratory and the CFD manipulations. The secondary data on the other hand, were obtained from published documents, textbooks related to the area under investigation and literatures that were relevant to thermodynamics of solar chimney. With the use of the information gathered from meetings held with the thesis supervisor and published literatures, this study took on the combined analytical and computational approach of research. By means of employing this combined approach, we were able to obtain the advantages of both analytical and computational approaches and overcome their limitations.

Quantitative data collection methods are centred on the quantification of relationships between variables. Quantitative data-gathering instruments establish relationship between measured variables. When these methods are used, the researcher is usually detached from the study and the final output is context-free. Measurement, numerical data and statistics are the main substance of quantitative instruments. With these instruments, an explicit description of data collection and analysis of procedures are necessary. An approach that is primarily deductive reasoning, it prefers the least complicated explanation and gives a statement of statistical probability. The quantitative approach is more on the detailed description of a phenomenon. It basically gives a generalization of the gathered data with tentative synthesized interpretations.

Quantitative approach is useful as it helps in preventing bias in gathering and presenting research data. Experimental data collection procedures create unique postulations that reality is objective and unitary, which can only be realized by means of transcending individual perspective. This phenomenon in turn should be discussed or explained by means of data analysis gathered through objective forms of measurement and observation. The quantitative data gathering methods are useful especially when a study needs to measure the cause and effect relationships evident between pre-selected and discrete variables. The purpose of the experimental approach is to avoid subjectivity by means of collecting and exploring information which describes the experience being studied.

3.7.1 Experimental Set-up

The diagram shown depicts the educational model fabricated to investigate how power can be extracted from the wind turbine to drive the coupled generator to generate electricity. The set-up was such that the base material next to the ground is an insulator wherein, four electrical heating elements were attached to an aluminium sheet metal mounted upon the insulator. The insulator is preferably painted black in colour to enhance better absorption of the solar heat and thus prevent heat loss to the ground or surrounding. Therefore, a concrete base would be better or suitable for this purpose in real-world design since their absorption and sustainability of heat are consistent and per excellent.

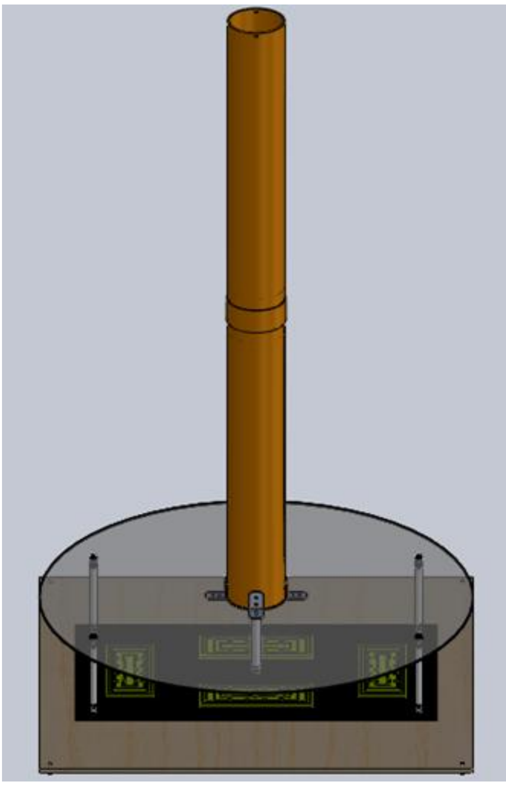

Figure 21 Educational model of SUTP

A Polyvinylchloride, PVC pipe acting as the solar tower is erected at the centre of the insulated sheet metal mounted on the ground (which is thus acting like the greenhouse heat exchanger) and is thoroughly clamped using strings and appropriate fasteners. The bottom open end of the pipe is elevated at a certain particular distance from the ground to minimize possible heat loss, thereby creating an open space for air to be heated inside the heat exchanger. This is done to facilitate free updraft of the hot air into the pipe.

A relatively large transparent Plexiglas cover is spread and stretched tightly above the ground-insulator-heating element around the pipe such that the pipe passes through a cut-out section over the centre of the Plexiglas having a diameter about the same as that of the pipe. The cut-out section of the canopy was machined to fit the pipe and glued firmly to prevent hot air from escaping or leak out the possible opening. The Plexiglas cover was positioned in such a way that it maintained a minimum height of $10cm$ above the ground, for the same reason, to ease the cycling and or up-drafting of air and minimize heat loss to the environment.

The pipe is painted black in approximation to the Stefan-Boltzmann black-body, since black body tends to be good absorber of heat. This pattern helps in maintaining a constant speed of the rising air and keeps the process as reversibly and adiabatic as possible and also acts as a “fuel.” This, thus help to maintain the air-flow at constant acceleration and in the upward direction, since hot air tends to rise above sea level to displace cold ones and fill the outer space. It is of course, this convectional induced flow phenomenon that drives the wind turbine inside the pipe.

The lower half of the solar tower or the pipe is fitted with a stepper D.C motor equipped with blades fabricated by rapid prototyping machine. The rising air creates thrust on the blades and turns them with a considerable force. The rotation of the blades moves its internal winding and coordinates the gear-box which reacts with the fixed magnets and generates electricity. This electricity passes through the motor output wires and can be used to power a light or an appliance or may be stored in accumulators or even pressure air storages for future use.

3.7.2 Experimental Procedure

The device was set-up as discussed above; such that, a fan anemometer was used in place of the propeller blades in order to measure the rotations per minute of the blades as well as its peripheral velocities.

The heating element mounted unto an aluminium sheet metal was used to produce electrical heat to energize the air inside the greenhouse heat exchanger. And the fan anemometer which was connected directly normal to the air-flow, read the rotational speed of the turbine blades as well as the peripheral velocity. The reading of these parameters were measured and recorded, for varying temperature differences.

In order to measure the output power of the wind turbine, the DC motor was connected to a load in the form of resistor. The optimum mass flow of the air at every differential increment in temperature were also measured and recorded.

T_u (K)	$\dot{m}$ (kg/s)	N (rpm)	ω (rad/s)	U (m/s)
298	1548.55	80.0	8.38	167.55
303	2280.98	150	15.71	314.16
313	3206.21	225	23.56	471.24
323	3837.67	300	31.42	628.32

Table 2 Table of reading 1

T_u (K)	ρ (Kg/m^3)	Q_{in} (MW)	$P_{o,ideal}$ (KW)	$\dot{I}_h$(W/m^2)
298	1.1574	14.09	27.72	934.065
303	1.1383	14.62	91.57	969.59
313	1.1019	14.62	271.38	969.59
323	1.0678	14.09	495.58	934.065

Table 3 Table of reading 2.

Below is a table of reading depicting the quantity as well as quality of power output the turbine can deliver, under the given conditions of temperature gradient and other solar parameters.

η (%)	ηII (%)	$\dot{m}_{opt}$ ($\frac{Kg}{s}$)	$P_{o,actual}$ (KW)
1.75	0.88	1548.55	24.62
5.63	0.89	2280.98	82.25
16.83	0.91	3206.21	246.02
32.05	0.91	3837.67	451.48

Table 4 Estimation of the quantity and quality of energy rate.

Consequently, below is the table of analysis used for computing the pressure losses in the tower. The kinematic viscosity used was taken to be constant for a temperature of 300K throughout. This was assumed because the temperature range used in the entire measurement varied sequentially from 298K to 323K at intervals of 5K. Thus;

R_e	Flow Type	λ	ξ	Δp (Pa)
5396090.58	Turbulent	0.00656	0.0821	13.60
8081655.70	Turbulent	0.00593	0.0742	27.12
11734730.05	Turbulent	0.00541	0.0676	50.42
14494641.08	Turbulent	0.00513	0.0641	70.71

Table 5 Calculation of Pressure losses in the Tower.

CHAPTER FOUR

4.1RESULTS AND DISCUSSION

The model (pilot plant experimentation) was solved for four different heat inputs and mathematical model of the results obtained as a function of independent parameters we shown graphically below. One of the many important parameters is the absolute temperature in the heating zone for the thermodynamic cycle taking place inside the solar tower. Thus, the temperature differences for all readings were manipulated to increase by 5℃ intervals.

4.1.1 Insolation (Global Radiation on Horizontal Surface)

As can be seen from the graphical representation below, the solar insolation tends to increase rise as the temperature of the greenhouse heat exchanger rises. This is not surprising, since the intensity of solar radiation results in heat transfer between the warm air and cold air. However, the region of temperature leverage (where there is no significant increase in solar insolation) accounts for both the low efficiency of the solar collector and possible uneven moisture content available in atmospheric air.

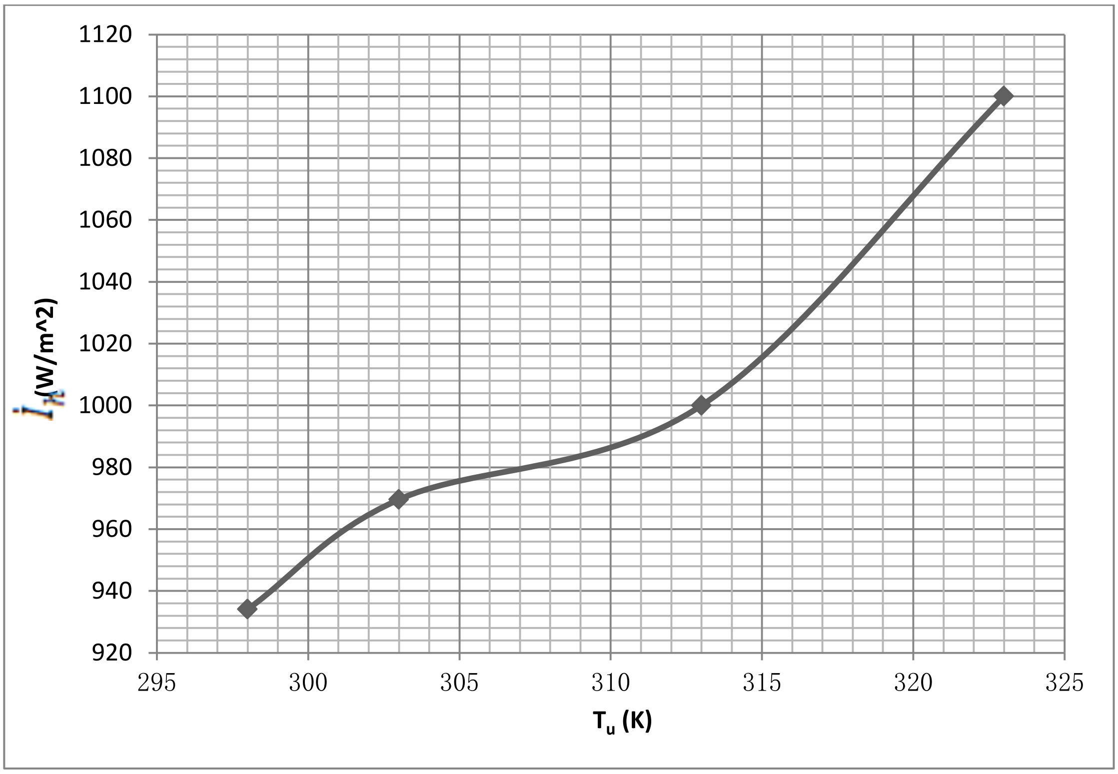

Figure 22 Characteristic curve of solar insolation with temperature variation.

4.1.2 Solar Heat

The solar heat (Heat input from solar radiation) is seen to distribute in such a symmetric form, since heat transfer with time is symmetrical. This is the quantity of heat needed to pass through the greenhouse and warm the air flow. It follows thus that the larger the heat absorbed by the collector, the larger the air mass flow, since it has been established that warm air has greater tendencies to displace cold air in space. The output curve envisaged that, the disorganized energy inherent in the heat flow will do well in converting much of the updraft into useful energy to drive the turbine, if the optical factors (such as transmittance, absorptance and emittance property of the Plexiglas) are so close to unity, in their entity.

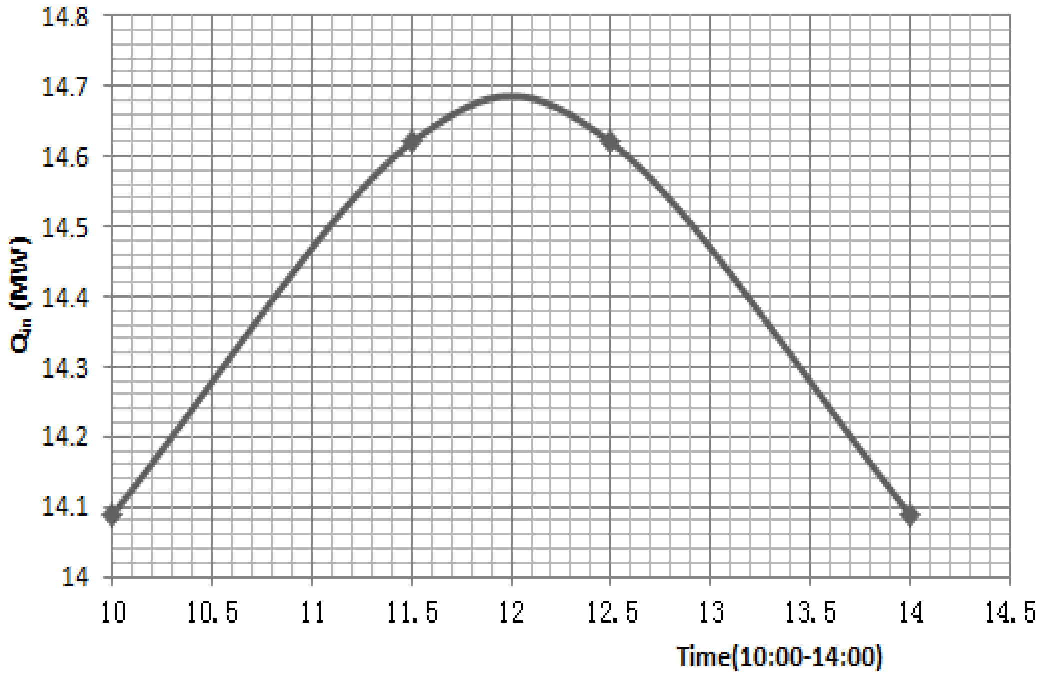

Figure 23 Solar heat distribution effects with time.

4.2 Characteristics Curve of Functions

Here, the results of the turbine performance as a function of important independent parameters such as mass flow of air, absolute temperature in the heating zone, wind speed as well as solar insolation were presented. Deductions from the curves are valuable tools in the design and improvement of the proposed lapses.

4.2.1 Output Power Vs Air Mass Flow

As can be seen below, the power output of the turbine unit is null when the air mass flow null. However, it reaches a maximum at a point where the air mass flow is optimized as shown in the mathematical model in chapter 3. The characteristic curve also reveals that the relationship between the output power and mass flow is non-linear; thereby re-assuring that the former bears a third power relationship with the latter. Each curve corresponds to a given temperature difference between the heating zone temperature and that of the dead state (environment).

The ideal power estimated without irreversibilities is plotted against the air mass flow and compared with the same effect an actual power (which takes into account the effect of all possible irreversibilities like friction loss, heat loss, pressure loss, gravitational loss etc) would produce, were presented in the below curve.

The curve reveals that, irreversibilities tend to reduce the performance of the turbine and therefore, the output power will be maximized at the point where the air mass flow is optimum. This is not the case for ideal power consideration, because there are no losses and the process is considered quasi-static. Thus, the ideal power which is the maximum theoretical value possible shows a continuous increase as the mass flow increases. The difference between both cases is represented by h_f , a factor called head loss due to irreversibility.

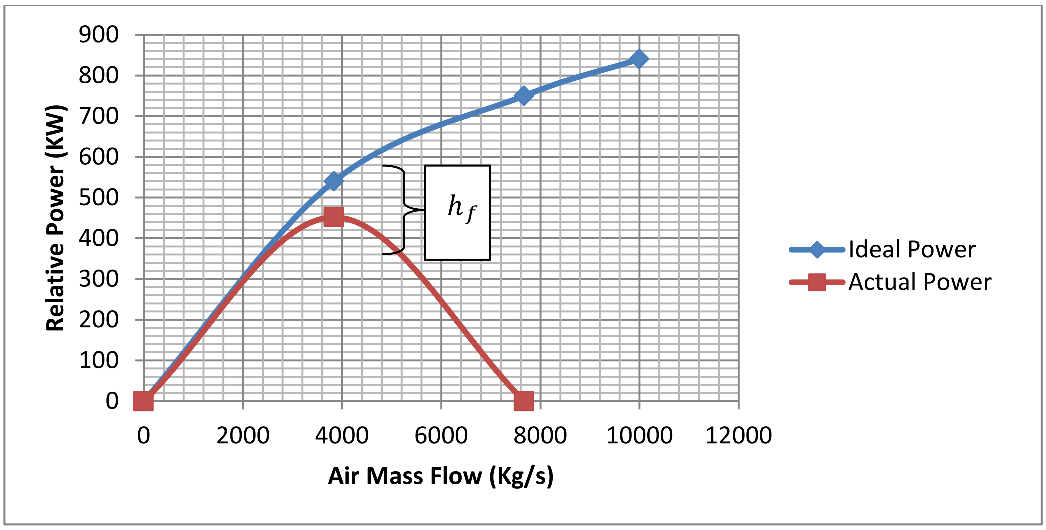

Figure 24 Power Output vs. Air Mass Flow.

4.2.2 Air Mass Flow Vs. Inner Temperature

The plot of air mass flow against the heating zone temperature shown below reveals that there is a distinct increment in the air mass flow as the temperature rises. And, it would be intuitive to deduce that the degree of disorderliness of the air flow will invariably boost the performance of the wind turbine. It can also be inferred from the air mass flow – temperature relationship that more air influx at elevated temperature will increase the exergy of the robust plant.

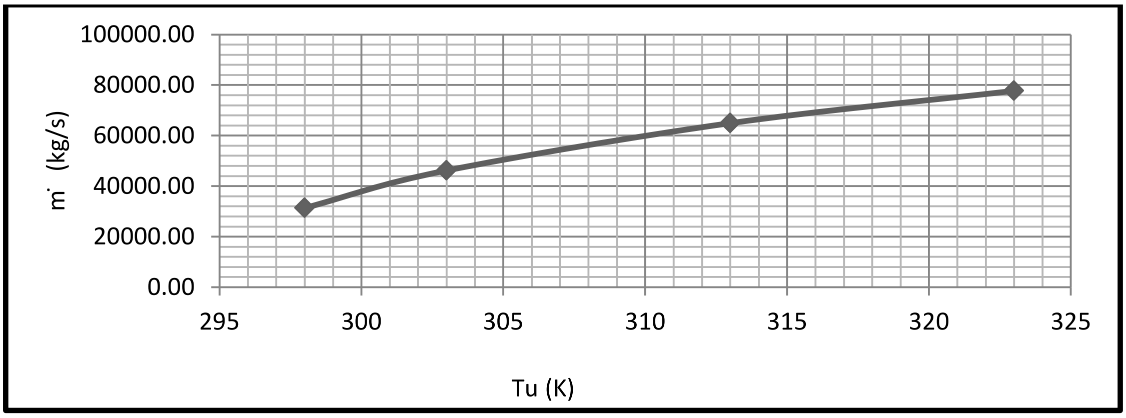

Figure 25 Air Mass Flow vs. Inner Temperature.

4.2.3 Output power Vs. Inner Temperature

The below power-temperature curve shows that as the temperature of the air rises, their rate of kinetic energy manifest into higher power output, therefore the more the entropy generation within the heating zone, the larger the performance of the wind turbine. The curve exhibits a steady increase of both quantities, which means more power will be delivered if the temperature keeps rising. This effect does not seem practical enough, since sun does not shine all year round. However, the excess energy produced during hotter season can be stored ideally in a compressed storage tank and use when needed.

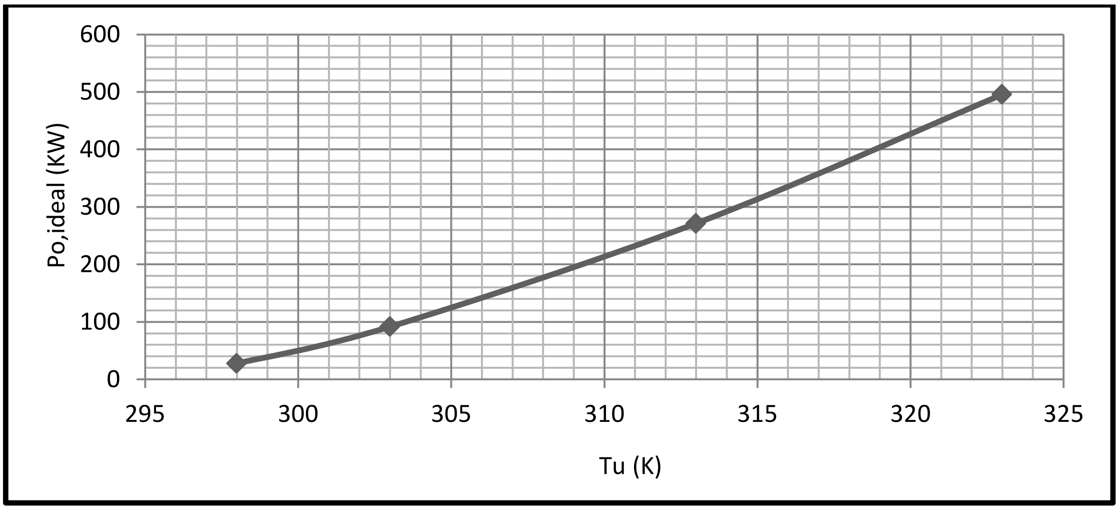

Figure 26 Output power Vs. Inner Temperature.

4.2.4 Output Power Vs. Global horizontal radiation

The characteristic curve shown below infer that regardless of whether the collector efficiency is high or low, at least to some appreciable extent, there will always be an increase in the amount of power delivered by the turbine. The constriction between $0{,}97 - 1{,}00 Wm^{-2}$ accounts for the possible losses inherent in the solar tower.

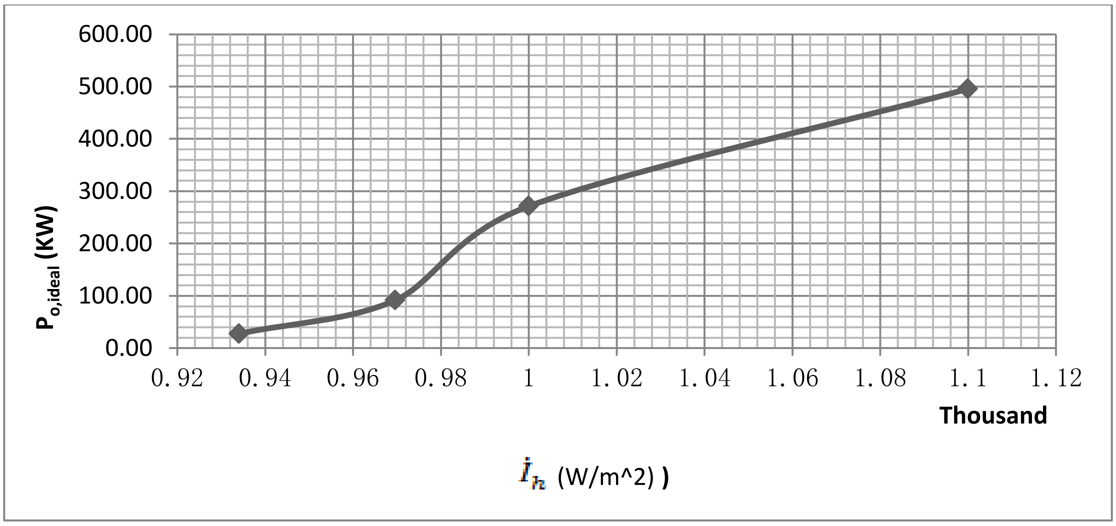

Figure 27 Ideal power vs. Insolation

4.2.5 Polytropic Relationship Between Pressure Drop and Air Mass Flow

Here, a plot of pressure drop against the air mass flow is investigated. It thus shows that the pressure drop becomes higher and higher as the air escapes against gravity. These losses is seen to be non-linear and in fact polytropic in form. It can be envisaged that, the polytropic index n varies between the inequality $1 < n < k$, where k is the isentropic (reversible adiabatic) index. Also, due to the presence of rough surfaces within the tower walls, a correction factor X has to be introduced to the right hand side to account for losses as shown; $\Delta P \propto X\dot{m}^n$.

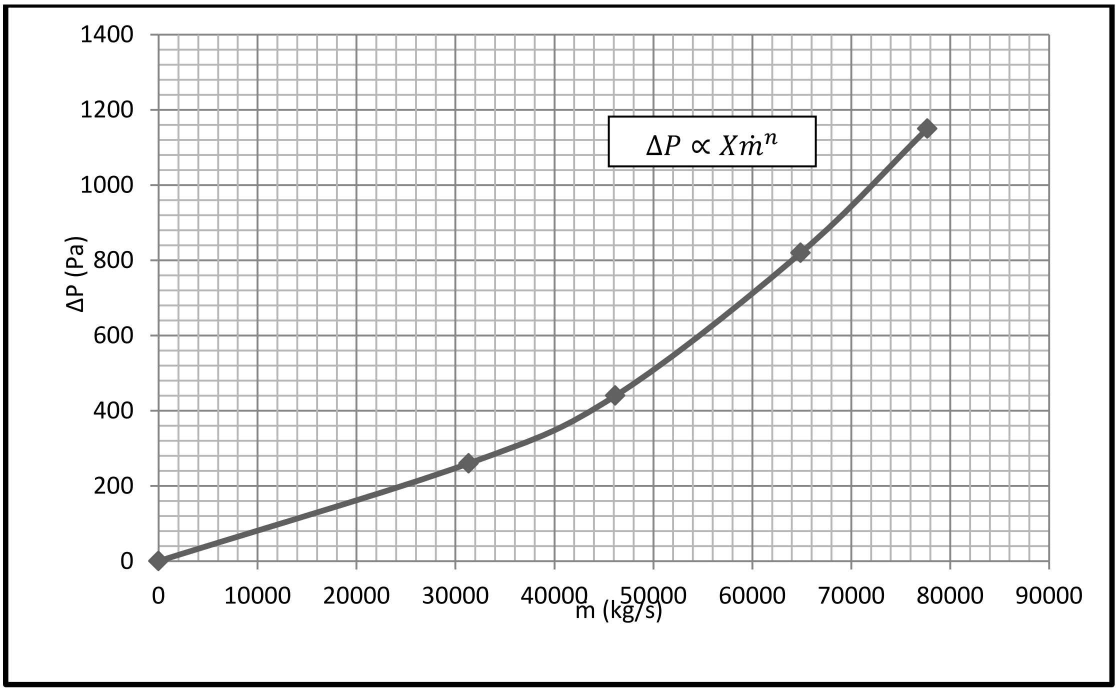

Figure 28 Characteristic curve of pressure drop Vs. air mass flow.

4.3 Efficiency and Exergy

Estimating the quantity of energy alone is not enough in modern day analysis, because not all the energy inherent in the turbine can be fully converted to useful work, hence the need to take into account the second-law efficiency (which is solely dependent on exergy). That is the quality of the energy is more important since it tells how much of the available energy can be used.

4.3.1 First-Law Efficiency

Here, the quantity of energy inherent in the turbine is presented in terms of its performance and plotted against the air mass flow. The curve shows that the efficiency of the turbine remains relatively constant and low with less mass flow. However, as the air mass flow becomes larger and larger, the efficiency rises correspondingly.

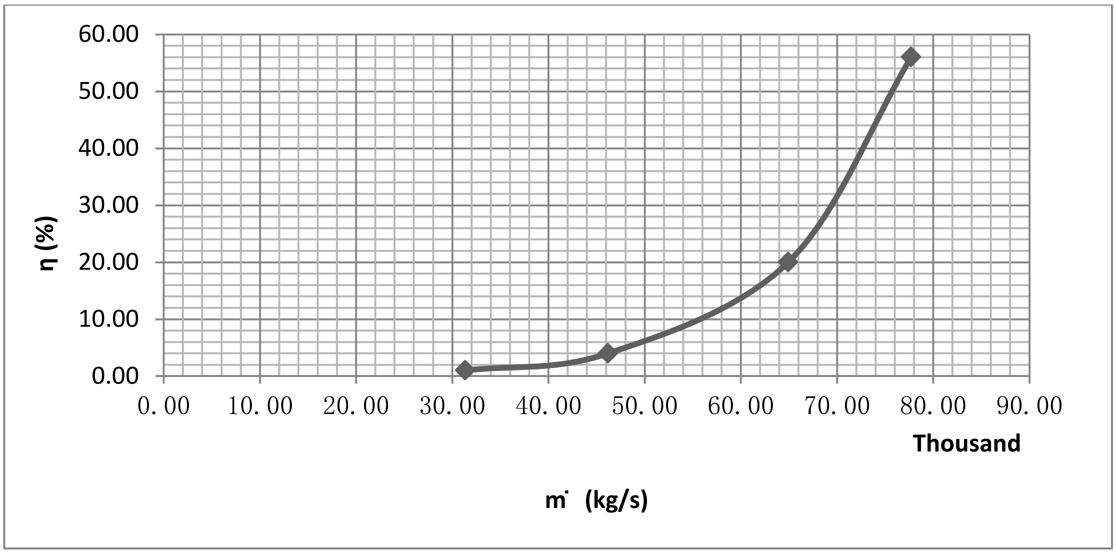

Figure 29 First-Law thermal efficiency vs. air mass flow.

4.3.2 Second-Law Efficiency

The available energy is evaluated here and plotted against the air-mass flow. The curve appears to be identical but, the efficiency in this case is much smaller than the former. This efficiency depicts the energy available for useful work to drive the generator. However, the magnitude of this efficiency would give an insight as to whether to embark upon constructing this power plant in a given location or not, because it takes into account the influence of ROI.

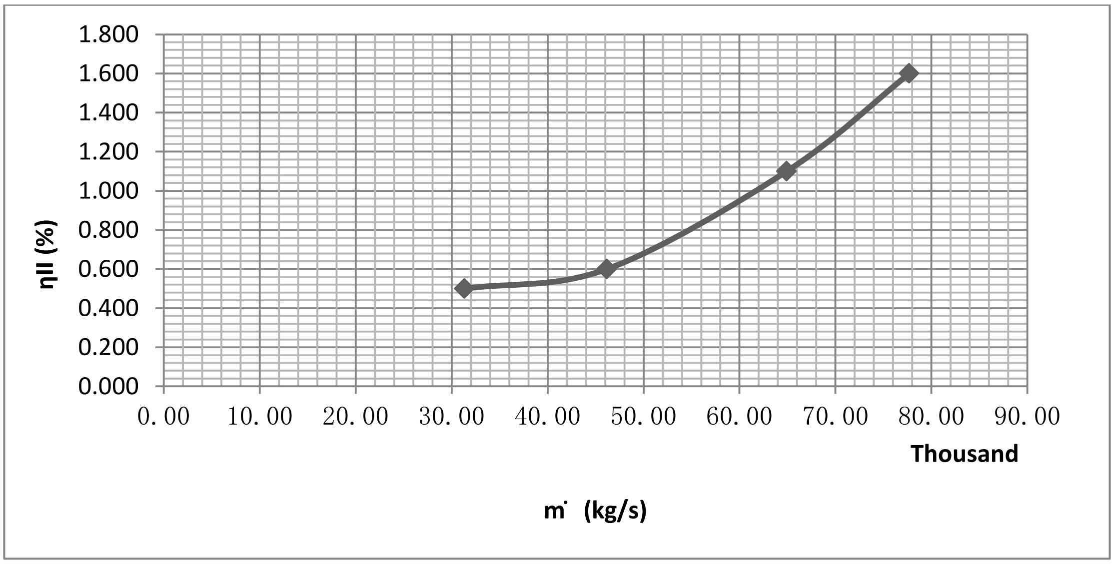

Figure 30 Second-Law thermal efficiency vs. air mass flow.

4.4 Influence of Air Humdity

The influence of humidity on the heating zone and corresponding performance characteristic effect is presented here. The parameters used herein are ideal parameters, and assumption was made to ignore the cooling tendencies caused by humidification. However, it is believed that overheating of the dry air before reaching the humidification zone would compensate for possible heat loss.

4.4.1 Influence of Humidity on Performance

As can be seen from the characteristic curve below, output power of the turbine under the influence of humidification is studied. The result showed that the performance of the solar updraft tower will be enhanced if humidified air is used as the heat transfer fluid. A comparison of performance between dry air and humid air revealed that the latter would yield a work potential of 45% which is considerably larger than the 32% obtained using dry air. However, the plot of figure 25 showed that the power output would increase slightly at low specific humidity and significantly when the humidity ratio is large. The most possible reason for this effect would be as a result of the turbulence or accelerated-buoyancy caused by the moist air.

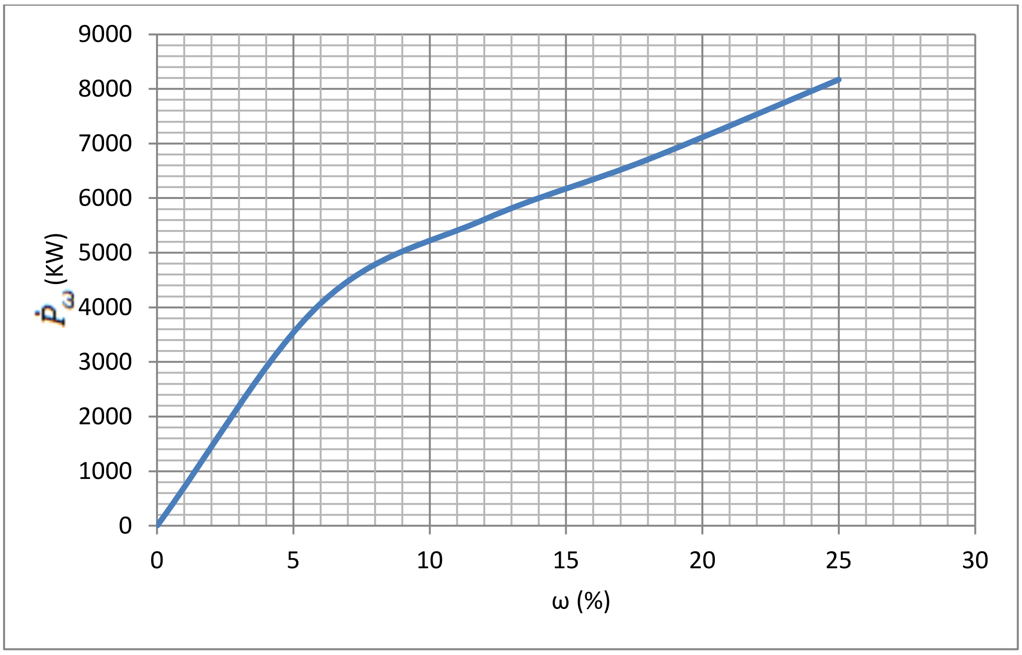

Figure 31 power output as a function of specific humidity.

4.4.2 Relative Power output characteristic curve

Humid air is evidently lighter than dry air and this can be of tremendous advantage when considering the buoyancy effect inside the tower. The reason being that, any slight increment in the air temperature yields a corresponding increase in its ability to hold water vapour. Therefore, humidified air enhanced buoyancy by accelerating faster than dry air. Although, this advantage would tend to reduce the heat flow because the process is only achievable by humidification-cooling effect. In order that the heat flow can be compensated for, it would be technically ideal to reduce the geodetic height of the tower.

The possible humidification effect in the heating zone is noticed around the turbine, because the humid air is more energized than dry air, and thus would produce a chaotic-like mass flow. The overall effect is a high percentage of energy output when compared with the dry air. The only shortcoming herein is heat loss compensation as well as tower height reduction.

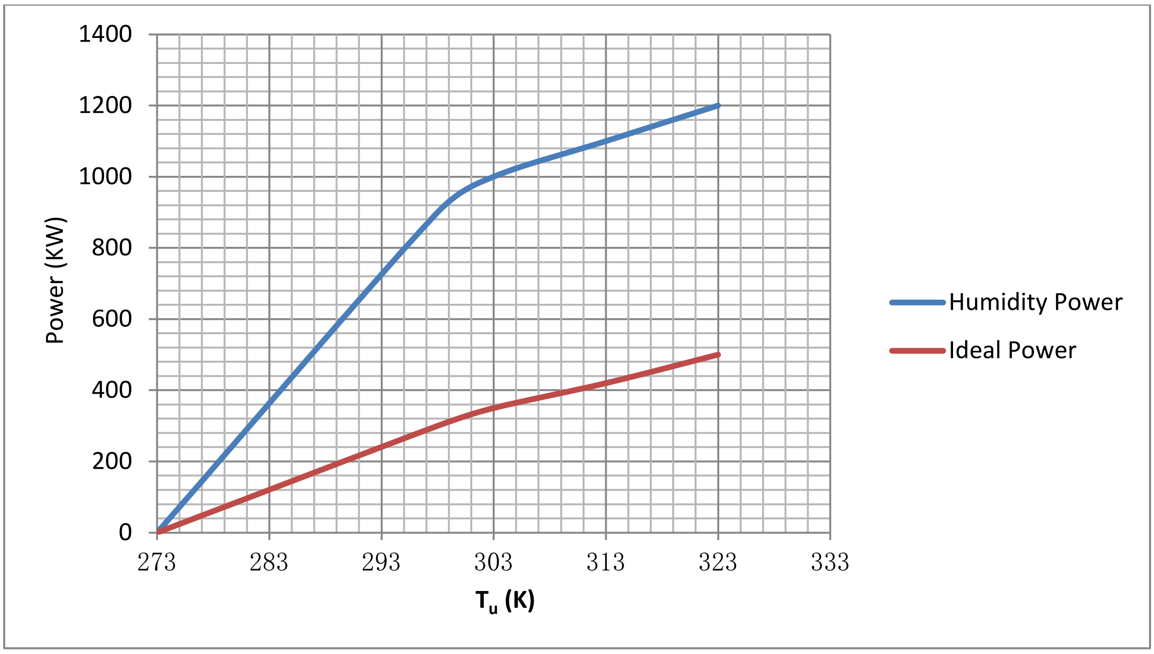

Figure 32 Relative power output as a function of temperature.

The graphical output above shows that at elevated temperatures, the performance of the turbine would be more pronounced with humidified air than dry air.

Therefore, it is necessary to know the air temperature and pressure under certain condition and evaluate the corresponding adiabatic saturation temperature and corresponding enthalpy from psychometric chart.

4. 5 Variation In Chimney Installations

It is not only a wise idea to seek possible alternatives in the design and construction of solar updrat towers but also cost comparative. Since, the investment cost alone has often made the solar technology a shelved invention when compared to other reasons. The vertical tube tower has proven it ability to deliver power as expected but in terms of cost and other constructional purposes, it would be emphasized that other variations exist as shown below.

4.5.1Principle of Professor Dubo

This variation was proposed to answer the relevant question of how well can the solar collector be positioned to extract the best possible energy from sunlight. The arrangement consist of a chimney mounted against a steep mountain in the south direction. Since it is evident that, mountains require no construction against drought and other possible air-borne constructional problems. Hence, cost of investment reduces considerably.

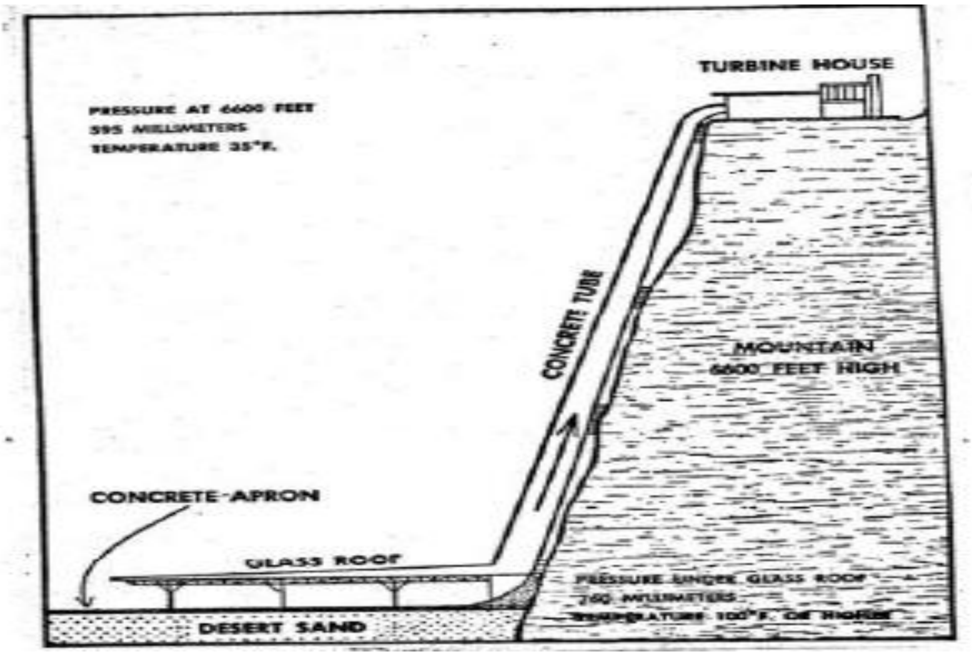

Figure 33. Professor Dubo power plant.

4.5.2 Gunther's Proposal

In 1931, German Gunther argued that, relying on mountain to build a solar chimney power plant is a creative idea. Thus, this mountain-chimney construction is similar to that proposed by professor Dubo, discussed above. The differences only arise from the position of the wind turbine house. Here, the turbine is positioned at the cross-section of the collector-tower interface. Both methods provide immediate alternatives and have been proven to offer competitive chimney construction costs and also improve resistance to mechanical loading.

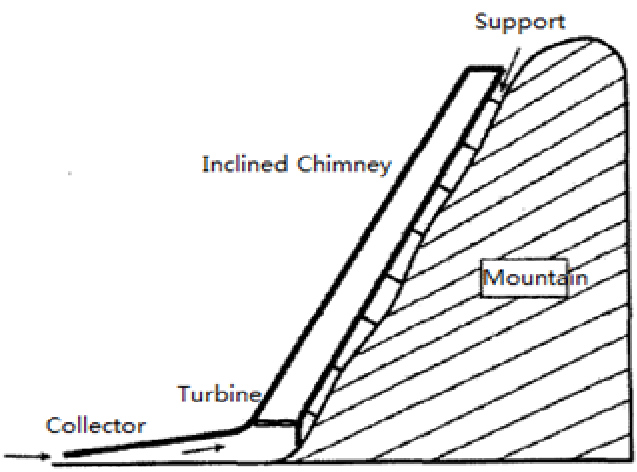

Figure 34 German Gunther's model.

4.5.3 Bilgen and Rheault Proposal

In 2005, Canadian E. Bilgen and J. Rheault proposed the construction of the solar collector in a sloppy and tapered (with high altitude) section. This idea is of course a brilliant and new idea because the angle of inclination would aid in providing sufficient and effective area of the collector to receive solar radiation, thereby improving the solar collector efficiency. And, as would be seen in the appendix, improving solar collector efficiency would increase the amount of useful heat needed to warm up the cold air.

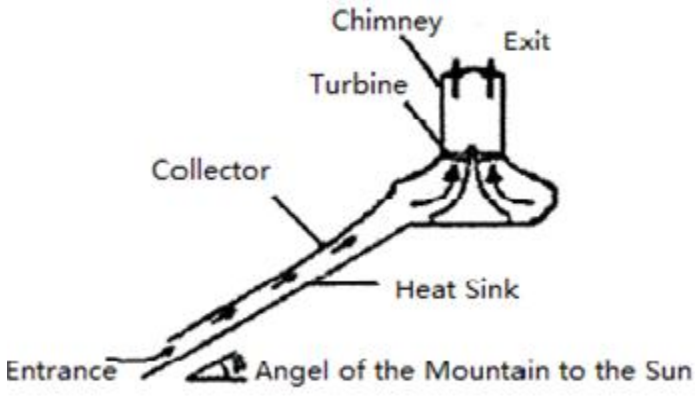

Figure 35 Bilgen and Rheault model.

4.5.4 Professor Papagcorsiou Proposal

In 2004, the Greek Professor Papagcorsiou proposed the concept of floating chimney which uses lighter gases (such as hydrogen, ammonia, helium etc.) to provide buoyancy and float in the atmosphere of the new chimney. Thus, the chimney builds up mainly by folded chain, foundation and chimney as shown below. The chimney consists of three layers from inside to outside in the order; inner tube, support ring and airbags. Flow channel from the inner cylinder role; rigid support ring increase the chimney-section stiffness; and light the gas inside the balloon to provide increased power compared to the chimney and resilience after the tilt.

This set up is entirely different in it mode of operation, and construction. But, provide an alternative to the conventional model.

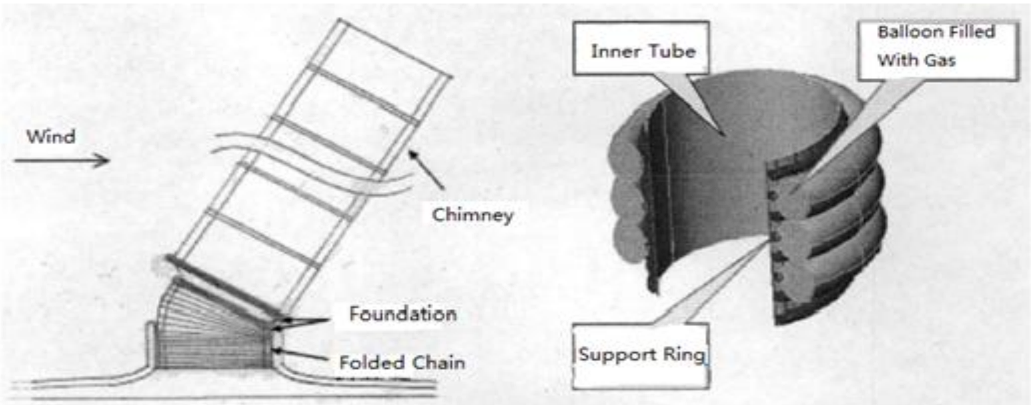

Figure 36 Professor Papagcorsiou model.

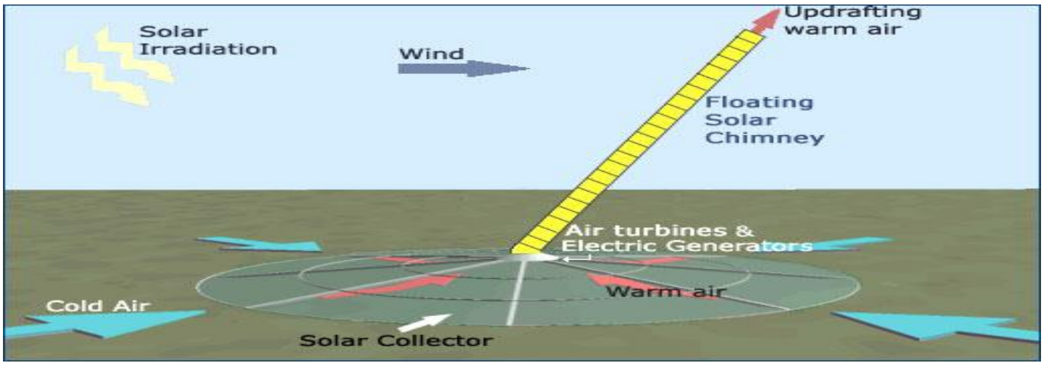

Figure 37 Pictorial view of the Papagcorsiou model.

4.5.5 Cave-Drilling Proposal

Another variation is that of a solar chimney power plant which employs drilling technology to dig a vertical duct inside a mountain. It consist of a combination of vertical cave and inclined tunnel. The sole purpose of this model is to improve the efficiency of the power plant in general.

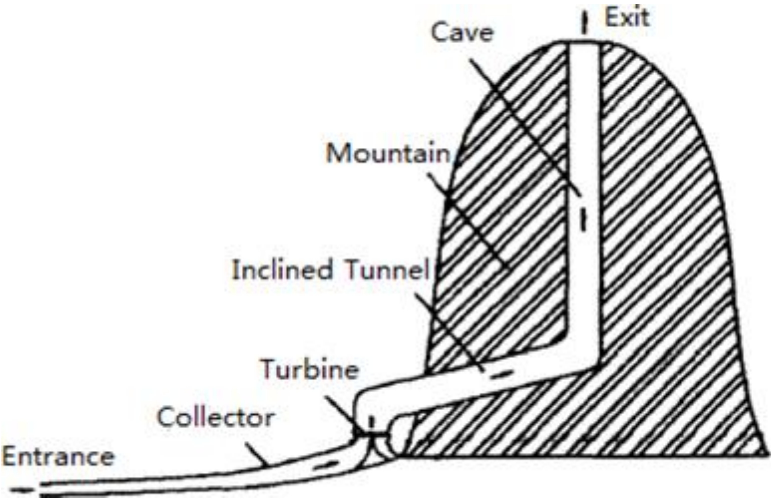

Figure 38 Cave-drilling model.

4.6 PRACTICAL APPLICATIONS

Even though the technology governing this robust design is straightforward, simple and technologically proven, and the investment cost has continued to pose a threat to its recognition. However, the configuration appears to have extensive potentials aside from the sole purpose it was perceived to serve; production of electricity. Different possible practical applications among much yet discovering potential include, thus;

4.6.1 Agricultural Sustainability

Naturally, ground water tends to evaporate into the atmosphere due to temperature difference. But, the presence of the greenhouse heat exchanger can serve a dual purpose by trapping this evaporated water and return it back to the topsoil. Thereby creating localized land moisture increase which in turn causes the soil under the collector suitable for agricultural purpose.

4.6.2 Environmental Safety Improvement

For instance, the solar updraft tower can be mounted in an urban area with reduced geodetic height. The tower could be fitted with particulate, carbon and many other air filters such that, the air buoyancy through the chimney can be filtered. The result would be a plus, since the air quality in the urban setting would be cleaned and environmentally safe.

4.6.3 Co-generation Purpose

Solar updraft tower can help in improving the efficiency of solar collectors or photovoltaic (PV) arrays when used together. Since, the excess heat generated by PV arrays often result to high temperatures which tend to reduce their power generation capacity significantly. The constant wind flow can air-cool the collectors while increasing the energetic output per area of land used, thereby making the solar updraft tower a more efficient prospect.

4.7 SOCIAL BENEFITS AND ECONOMIC FEASIBILITY

4.7.1 Social Benefits

A properly designed solar updraft tower will not only serve its primary function; generation or power, but also provide a number of advantages to the society where it is built in terms of noise and fumes exhaust reduction. The proposed social benefits are;

1. The areas beneath the greenhouse heat exchanger add sufficiently condensed water to the supposedly unproductive land.
2. Solar updraft tower built in the desert stimulates plant growth.
3. It would transform the desert into arable land.
4. Condensation created at nights due to temperature difference between the air and ground invigorates the soil with moisture.
5. A solar updraft tower standing 1000m tall could provide tourist attraction, thereby promoting the awareness of its location and also generate a commendable ROI by adding to the revenue of the region.

4.7.1 Economic Feasibility

Among the crucial factor to consider when planning to build a solar updraft plant on commercial basis is its feasibility, thus;

1. The investment cost is huge.
2. Operational cost is relatively low.
3. Maintenance cost can be averted, if properly designed.
4. The plant's efficiency is discouraging compared to cost and output of conventional power generation plants, but would be ideal for third world countries with sizable land space.

CHAPTER FIVE

5.1 SUMMARY, CONCLUSION AND RECOMMENDATION

5.1.1 Summary

The thermodynamic theory (based on mass, energy and impulse balance equations) governing the working sequence of the solar updraft tower has been thoroughly investigated. And both the energy and exergy aspect of the design were examined in order that the performance of the wind turbine can be analyzed. Technical thermodynamic analysis of the solar collector (greenhouse heat exchanger) as well as that of the solar tower has been validated. The influence of air humidity on the greenhouse heat exchanger and possible humidification effects around the heating zone has been presented. The solar intensity at a given place to a horizontal area has been calculated for the educational model of interest. Also, a mathematical model was written to estimate all important parameters and their graphical output of characteristics presented. The irreversibilities inherent in the design (such as friction losses, heat losses, pressure losses of the solar tower) were calculated.

The best possible way to design the wind turbine unit in order to maximize the output power relative to the blades tip-speed ratio was sought and the principles of flow mechanics were not violated. However, a small model tower for educational application was fabricated so as to solve a hands-on task related to a commercial prototype and measurements were taken for varying conditions. Wherein, a CAD-model, drawings and animations of movable parts like the wind turbine rotational effect during operation were also presented.

The solar updraft tower is a promising project if embarked upon, because its principle is based on proven and simple technology. It also requires no maintenance cost in spite of its high investment cost and the return on investment, ROI would make a comeback.

5.1.2 Conclusion

It can be inferred from the results obtained and graphical output of characteristics that the robust design would function at its best if the temperature difference is as large as possible. Since, the hotter air tends to be more energetic and create a stack effect along the tower. It was also shown that at elevated temperatures, the mass flow becomes larger that it produces a thrust of higher magnitude on the turbine blades which in turn improves its performance.

The performance of the turbine both for ideal and actual cases was presented. The power output was found to be dependent on the third power of the air mass flow and thus upon the tip-speed ratio. The effects of losses were considered and insight was gained into improving the design to minimise such irreversibilities. The solar insolation intensity determines how intense the temperature would be, which showed that the solar collector's efficiency plays a vital role to achieve a better performance. The influence of humidity was found to accelerate the buoyancy or updraft of the air inside the tower, thereby improving the performance of the turbine. Although, this effect is not practical thus, the shortcoming can be averted by reducing the height of the tower.

Consequently, the mechanical strength of the structure can be assured by employing the professor Dubo, cave-drilling and or Rheault's model discussed.

To sum up, the overall performance of the robust design can be achieved if the area under the heat exchanger is as large as possible and the tower height as tall as possible.

5.1.3 Recommendation

Based upon the research findings, I recommend that;

1. Optimization should be directed towards increasing the enthalpy by ensuring ΔT is as large as possible.
2. The solar collector should be of superior quality with high concentration efficiency. Since, it has been validated that, the heat exchanger would transmit heat of higher intensity if its optical properties are advantageous.
3. The physical and chemical properties of the heat transfer fluid (such as density, specific enthalpy, moisture content, velocity and mass flow) should be adequately exploited.
4. The top of the tower can be coned such that external wind flow could aid hot air drag from the tower.
5. Perhaps, a second wind turbine could be coupled at the top of the tower to produce additional updraft.

SOURCES

- [Katherine Hamnett]-------- www.katherinehamnett.com
- [MEF] -------------------Michigan Engineering Forum (forum.engin.umich.edu), 06.04.2011
- [Fullwiki]---------------------- www.fullwiki.org
- [ESRI] ------------------------- webhelp.esri.com
- [RRE] -------------------------- Renewable Resources Engineering Lecture note.
- [R.Spencer] ------------------- www.drroyspencer.com
- [COL-ANT] ------------------ Colonizaantarctica.blogspot.com, 06.07.2011
- [Hyperphysics] --------------- hyperphysics.phy-astr.gsu.edu
- [UWSP] ------------------------ www.uwsp.edu

REFERENCES

1. Petela, R. Engineering thermodynamics of thermal radiation. *For Solar Power Utilization*, 10/11, 265-331, 2010.
2. Moran, M. J., and H. N. Shapiro. *Fundamentals of Engineering Thermodynamics, 2nd ed., John Wiley & Sons, New York, 1992.*
3. Holman, J. P. *Heat Transfer*, 10th ed., McGraw-Hill, New York, 2009.
4. J.F. Douhglas, J.M. Gasiorek and J.A. Swaffield. Fluid Mechanics, 4th ed., *Compressible flows through rotodynamic machines.* 708-822, 2001.
5. Tarik Al.Shemmeri. "Engineering Thermodynamics", 38-55, 2010.
6. R. Joel. "Basic Engineering Thermodynamics", 5th ed., Longman asia ltd, hong kong, 1996.
7. Haaf W., Freidrich K., Mayr G., and J. Schlaich. *Solar Chimneys Part 1,* Principle and Construction of the Pilot Plant in Manzanares, "*International Journal of Solar Energy",* Vol. 2, 1983.
8. Haaf W., *Solar Chimneys Part 2,* Principle and Construction of the Pilot Plant in Manzanares, "*International Journal of Solar Energy",* Vol. 2, 1984.
9. J. A. Duffie and W.A. Beckman, *Solar Engineering of Thermal Processes,* 2nd Edition, John Wiley & Sons, Inc, 1991.
10. A.J. Gannon and Von Backström W., *"Solar Chimney Circle Analysis with System Losses and Solar Collector Performance",* Solar 2000, 2000.
11. http://www.enviromission.com.au/EVM/content/technology_project.html
12. T. Satsuma, *Solar Updraft Towers, "Symposium Presentation 5",* May 5, 2009.
13. Schlaich J., Bergermann R., Schiel W., Weinrebe G. *"Design of a commercial solar updraft systems"*- Utilization of Solar Induced Convective Flows for Power Generation, Germany: Stuttgart 2004. (Unreleased text).
14. Ninić N. Available energy of the air in solar chimneys and the possibility of its ground level concentration. Solar Energy 2006 (Article in press).
15. Schlaich J. The solar chimney: Electricity from the sun. In: Maurer C, editor. Germany: Geislingen; 1995.
16. Bansal, N.K.; Mathur, R.; Bhandari, M.S. 1993.Solar chimney for enhanced stack ventilation. Building and Environment, Vol. 28, No. 3, pp.373-377.
17. Sandberg, M.; Mosfegh, B. 1996. Investigation of fluid flow and heat transfer in a vertical channel heated from one side by PV elements.
18. Proceedings of The Fourth Renewable Energy Congress, Denver, USA, (1996)

APPENDIX

Here, I present a detailed analysis of the solar updraft tower power plant using modified dimensions extracted from the 1982 prototype in Spain. The aim is to evaluate the performance of the turbine unit and to validate the thermodynamical relations associated with it. Thus, the used parameters are;

$D = 300m; \quad d = 20m;$

$A_o = \frac{\pi}{4}.d^2 = 314{,}16m^2;$

$\emptyset_o = 30\%; \quad \emptyset_u = 60\%$

$P_{g1} = P_{sat\ @50℃} = 15{,}25KPa$

$P_{g2} = P_{sat\ @20℃} = 5{,}38KPa$

$h_{g1} = 2509{,}25KJ/Kg$

$h_{g2} = 1805{,}55KJ/Kg$

$\xi = 0.0641; \quad \lambda = 0.00513$

$H = 200m; \quad \nu = 15.68 \times 10^{-6} m^2 s^{-1}$

$\Delta T = 30K; \quad T_u = 323K$

$T_o = 293K; \quad P_u = 101325Pa;$

$R_s = 287JKg^{-1}K^{-1}$; $R_\omega = 461JKg^{-1}K^{-1}$

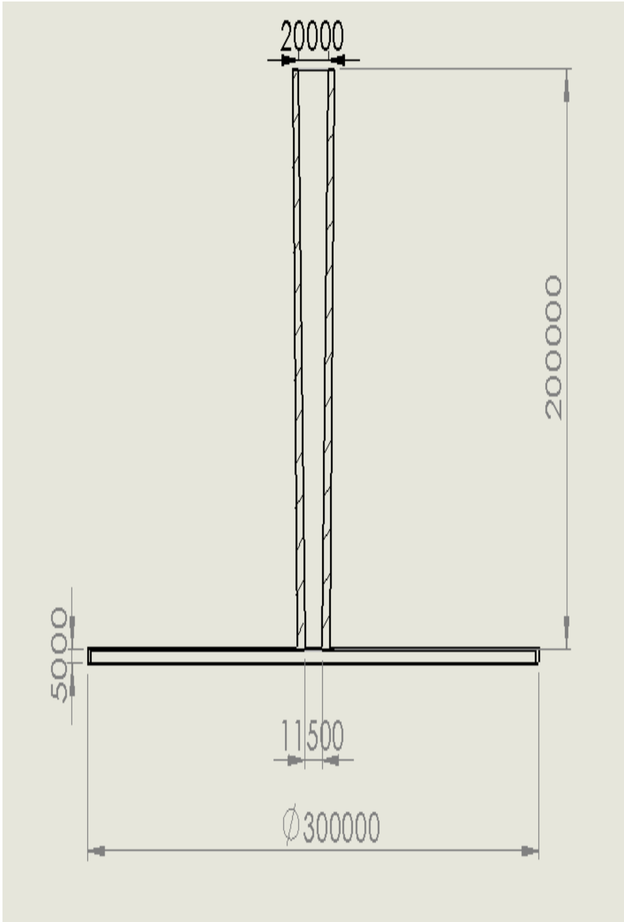

Figure 39 Typical model dimension

Now;

$\gamma = \frac{k-1}{k} = \frac{2}{7}$

$B = e^{-\frac{gz}{R_s T}} = e^{-\frac{9{,}81ms^{-2}.200m}{287JKg^{-1}K^{-1}.293K}} = 0{,}9769$

$C = \frac{R_s}{P_u B^{(1-\gamma)} A_o} = \frac{287JKg^{-1}K^{-1}}{101325Nm^{-2}.0{,}9769^{(1-\frac{2}{7})}.314{,}16m^2} = 9{,}17 \times 10^{-6}$

$K = \frac{7}{2} R_s (B^\gamma - 1) = \frac{7}{2}.287JKg^{-1}K^{-1}.\left(0{,}9769^{\frac{2}{7}} - 1\right) = -6.67398 < 0$

Then;

1. $\dot{m}_{opt} = \frac{1}{CT_u}.\sqrt{-\frac{2}{3}(KT_u + gH)}$

$= \frac{1}{9,17\times10^{-6}.323K}\sqrt{-\frac{2}{3}(-6.67398.323K + 9,81ms^{-2}.200m)}$

$\therefore\ \dot{m}_{opt} = 3837,67kgs^{-1}$

2. $\dot{P}_{output,ideal} = \frac{1}{CT_u}.\left[-\frac{2}{3}(KT_u + gH)\right]^{3/2}$

$= \frac{1}{9,17\times10^{-6}.323K}.[-\frac{2}{3}(-6.67398.323K + 9,81ms^{-2}.200m)]^{3/2}$

$\therefore\ \dot{P}_{output,ideal} = 495,58KW$

3. $\dot{P}_{output,actual} = \frac{1}{CT_u}.\left[-\frac{2}{3}\left(\frac{(KT_u+gH)}{(1+\xi)}\right)\right]^{3/2}$

$= \frac{1}{9,17\times10^{-6}.323K}.[\frac{-\frac{2}{3}(-6.67398.323K+9,81ms^{-2}.200m)}{(1+0.0641)}]^{3/2}$

$\therefore\ \dot{P}_{output,actual} = 451,48KW$

4. $\dot{P}_{\omega} = \dot{m}\left[\frac{7}{2}R_s(T_o - T_u) + (\omega_1 h_{g1} - \omega_2 h_{g2}) + \frac{1}{2}w_o^2 + gH\right]$

Where;

$\omega_1 = 0.622\left(\frac{P_v}{P-P_v}\right) = 0.622\left(\frac{\emptyset_u P_{g1}}{P-\emptyset_u P_{g1}}\right) = 0,622\left(\frac{0,6.15250Pa}{92175Pa}\right) = 0,062$

$\omega_2 = 0.622\left(\frac{P_v}{P-P_v}\right) = 0.622\left(\frac{\emptyset_o P_{g2}}{P-\emptyset_o P_{g2}}\right) = 0,622\left(\frac{0,3.5380Pa}{99711Pa}\right) = 0,010$

$\dot{m}_T = \dot{m} + \dot{m}_W = \frac{P_u}{R_\omega T_u}.A_o.w_o + \dot{m}(\omega_2 - \omega_1) = 2876,6Kgs^{-1}$

Thence;

$\dot{P}_{\omega} = \dot{m}_T\left[\frac{7}{2}R_\omega(T_o - T_u) + \left(\omega_1 h_{g1} - \omega_2 h_{g2}\right) + \frac{1}{2}w_o^2 + gH\right]$

$= 2876,6\left[\frac{7}{2}.0,461(323 - 293) + (0,062.2509,25 - 0,010.1805,55) + \frac{1}{2}11,36^2 + 9,81.200\right]$

$= 2876,6(48,405 + 132,4995 + 64,5248 + 1962)$

$\therefore\ \dot{P}_{\omega} = 6350\text{KW}$

Remarks; It can be concluded that humidified air will improve the performance of the turbine. This is not surprising since the density of humid air is far less than that of dry air and its specific gas constant is significantly larger than the latter. However, in order to get rid of the humidification-cooling effect, the geodetic height of the tower has to be reduced considerably. The efficiency generated by humidifying the air can be computed thus;

5. $\eta_\omega = \frac{\dot{P}_\omega}{\dot{Q}_{in}} = \frac{6350\text{KW}}{14,09\times10^3KW}\times 100\% = 45\%$

6. $\eta_T = \frac{\dot{P}_{output}}{\dot{Q}_{in}} = \frac{\frac{1}{CT_u}\left[-\frac{2}{3}\left(\frac{(KT_u+gH)}{(1+\xi)}\right)\right]^{3/2}}{\dot{m}\frac{7}{2}R_s(T_u-T_o)} = \frac{451{,}48KW}{14{,}09\times10^3KW} \times 100\% = 32{,}05\%$

7. $\eta_{II} = \frac{\left[-\frac{2}{3}\left(\frac{(KT_u+gH)}{(1+\xi)}\right)\right]^{3/2}}{\left[-\frac{2}{3}(KT_u+gH)\right]^{3/2}} = \frac{451{,}48KW-\sum losses}{495{,}58KW} \times 100\% = (91{,}1-b)\%$

However, $b\%$ is a fraction of the possible losses apart from the frictional loss considered for this analysis. It could be as large as possible and could range from transmission loss to conversion loss among many other possibilities.

8. $\eta_c = \left(1-\frac{T_o}{T_u}\right).\left(1-\frac{\sigma T_u^4}{\dot{I}_h.\eta_{conc}}\right)$

$= \left(1-\frac{293K}{323K}\right).\left(1-\frac{5{,}6703\times10^{-8}Wm^{-2}K^{-4}.323^4K^4}{934{,}065Wm^{-2}.0{,}08}\right) = 0{,}0929.0{,}97 = 0{,}089$

$\therefore\ \eta_c = 9{,}0\%$

It can be inferred from this calculation that, the efficiency of the collectors would hinder the performance of the turbine if it were to be used alone. This means that, the solar updraft tower is a commendable energy source than the collectors as a stand alone technology.

VITA

BIO-DATA

Name: Babaleye Ahmed Oyeyinka
Gender: Male
Nationality: Nigerian
Date of Birth: 29th Dec. 1984
E-mail: ao.babaleye@stud.fh-sm.de; ahmed.babaleye@student.saimia.fi
Mobile Tel. No.: +4917639133887; +358445423126.

CAREER OBJECTIVE

- To contribute immensely in the research area of my specialization, employing the latest engineering software and equipment in solving both numerical and analytical problems, thereby contributing to knowledge in my field especially in presentation of papers/ journals in conferences and seminars.
- To build a long-term teaching and research career in the field of fluid and thermal sciences with keen interest on renewable resources engineering.

EDUCATIONAL BACKGROUND

- **B.Eng., Mechanical Engineering (Dual Degree)** **(CGPA: 4.00/5.00)**
  - *University of Applied Sciences, Schmalkalden, Germany.* 2010 – 2011
  - *Saimaa University of Applied Science, Finland.* 2008 – 2011

ACADEMIC RESEARCH AND THESIS EXPERIENCE

1. T. Bai, **A.O. Babaleye**, 2011. “Design and Thermodynamic analysis of a Solar Updraft
2. Tower” (Unpublished Bachelors Thesis).
3. T. Bai, **A.O. Babaleye**, 2010. “Computational Fluid Dynamics (CFD) analysis of Segner Wheel” (Engineering Project, Unpublished).
4. B. Tianfu, **A.O. Babaleye** 2010. “Improvement on the design of a cam follower apparatus”. (Simulation of Motion, Term paper).
5. H. A. Latif, **A.O. Babaleye**, 2009. “Research on intelligence machine production line using Simatic Manager” (Automation Laboratories, Titled Project C on Transcript).
6. C. Kingsley, **A.O. Babaleye**, G.M. Bekele, 2009. “Pneumatic control of industrial cylinders using PLC” (Electro-pneumatics research work, Titled Project C on Transcript).
7. Bai T. Fu, **A.O. Babaleye,** 2010. “Turbulence Modelling of a Tapered Section Industrial Pipeline” (Hydraulics Term Paper).
8. L.O. Avelar, **A.O. Babaleye**, 2010. “Effect of Temperature Distribution on a copper shell element” (Numerical Heat Transfer Simulation Project).
9. W. Teriba, **A.O. Babaleye**, 2006. “Fabrication of fixed and fluidized bed apparatus (Unpublished ND Thesis).