The Effect Constant and Non Constant Pressure Driving Force on Energy output in a Solar Chimney Power Plant

by

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Abstract

Solar energy has a great potential for the future; it is free, its supplies are unlimited, it does not pollute the environment and cannot be controlled by one industry. Currently, the use of solar energy as an alternative source through solar radiation is seriously constrained by low efficiency of solar cells. In solar chimney, as air density inside the system is less dense than that of the environment at the same height, natural convection affected by buoyancy which acts as driving force comes into existence. All models so far developed have only considered constant driving pressure systems. But there are also non constant driving pressure systems whose pressure driving force have not been investigated. The objectives of this study were to determine the effect of constant and non constant pressure driving force in a solar chimney power plant and to assess the effect of air velocity on the power output for constant and non constant pressure driving system. Methodology used include the use of mathematical equations of continuity, momentum and energy which were solved numerically using finite difference method. The effect of the driving force on power output was determined through graphs.The highest temperature and velocity in the chimney, of 19^0C and 10m/s, respectively were used to estimate the driving force and power output in a solar chimney power systems. Another result obtained is that the higher the driving force, the higher the power output. The results were validated by measurements from other models. The implementation of this study is of great significance for the development of new energy resources and the commercialization of power generating systems. It may help developing countries to promote rapid development of the solar hot air-flows power generation.

Chapter 1

INTRODUCTION

1.1 Background to The Study

Energy is central to sustainable development and poverty reduction efforts. It affects all aspects of development such as social, economic, and environmental-including livelihoods, access to water, agricultural productivity, health, population levels, education and gender-related issues. None of any development goals can be met without major improvement in the quality and quantity of energy services in any country[15].

Current electricity production from fossil fuels such as natural gas, oil or coal is damaging to the environment and bears the limitation that it relies upon non-renewable energy sources. Many developing Countries cannot afford these conventional energy sources, and in some of these locations nuclear power is considered an unacceptable risk[28].

It has been shown that lack of energy may be connected to poverty. Even in today's world, with all of the vast technological advancements and improvements, there are still people who live in darkness at night and use candle light or kerosine lamps[5]. These people have the knowledge that electricity exists; however, the areas in which they live lack the infrastructure and resources for such an amenity. Also, throughout the world, the demand for useable energy is increasing rapidly, with electricity being the energy of choice. The need for an environmentally friendly and cost effective electricity generating scheme is thus obvious. A possible solution to the ever increasing challenge is solar energy. It is an abundant, renewable source of energy that only needs to be harnessed to be of use to man[28]. Solar power plants in use in the world are equipped to transform solar radiation into electrical energy[28].

Mathematical models find use as tools to simulate real life situations and to forecast future behaviour in the physical and biological sciences, business and other fields of study. In recent years, quite a lot of work has been done in solar energy in the developed countries unlike in the developing ones[32]. Indeed some of the developed Countries for along time have quite expensive radiation measuring equipment installed at various local stations for meteorological purposes[32].

As a developing country, Kenya is rapidly increasing its energy consumption but is short on energy supplies. Energy is the motive force of economic development and the demand gradually increases with population expansion and industrial development. It is therefore a matter of interest to assess the significance of solar energy and its utilization in different fields of applications.

The demand for renewable and clean energy is increasing. In recent years, the development of new technologies utilizing renewable and clean energy has become an important area of worldwide research[42]. Solar energy is a renewable and clean energy source. Of the many techniques utilizing solar energy, the most attractive ones seem to be: solar photovoltaic technology and solar concentrating thermal power technologies such as solar parabolic trough power systems , solar tower power systems, dish power systems, central receiver solar power plants, linear fresnel reflector power system and solar pond power plants. However, the cost of investment and running these power technologies remain high[42].

There are several alternative sources of energy that can generate electricity with very few or no negative side effects to the planet. These sources, unlike nuclear and fuels, are nearly limitless[22]. Some of these sources are even consistent enough to be used for baseload generation[22]. These sources include hydro-electric, whether it is from dams, the currents in a river, or the waves in the ocean, power from water is consistent and offers the ability to provide, if not constant, at least predictable or controllable energy[22]. Another renewable source, though not as easily accessible as hydro sources, is geothermal. Wind power on the other hand is much more available the world over, though it is not easily predictable. If we are to break our dependence on fossil fuels without the help of the nuclear power, we must seek out a steady source that can be easily controlled and harnessed and done so in a predictable fashion. The only source capable of doing this is the sun. Solar energy can be harnessed in many ways. In photovoltaic cells also called PV cells or solar, are made up of silicon. Electricity is produced when sunlight strikes the solar cells, causing the electrons to move a round. The action of electrons starts an electric current.

The photovoltaic power plants are few today and the systems are expensive[21]. Solar thermal systems on the other hand use solar energy to produce electricity, but in a different way. Most solar thermal systems use a solar collector with a mirrored surface to focus sunlight onto a receiver that heats a liquid. The super-heated liquid is used to make steam to produce electricity[21]. Solar energy has a great potential for the future; it is free, its supplies are unlimited, it does not pollute the environment and cannot be controlled by one industry[21].

This work therefore focussed on using solar chimney power plant(SCPP) to harness the sun's enormous power, by determining the effect of constant and non constant pressure driving force in a solar chimney power plant. Inside solar chimney power plant air is less dense than the atmospheric air outside. The density difference of the air caused by temperature rise in the collector work as a driving force. Air moves in and out of the solar chimney system continuously, driven by the pressure difference between the inside and outside. This pressure difference is called the driving pressure or the driving force or the buoyancy force. If an axis-based turbine is placed inside the chimney where there is a large pressure drop, the potential and heat energy of the air can be converted into kinetic energy and ultimately into electric energy. Solar chimney power plant requires relatively low technology hence suitable for remote regions in developing Countries.

In Kenya, like in most developing African Countries, the energy sector is dominated by traditional energy sources such as fuel. Modern energy: electricity, petroleum and infrastructure for energy supply exists mainly in urban areas. For this reason, majority of the population living in rural areas have little access to modern energy.

Adequate and reliable supply of energy is crucial for social and economic development of any Country. Easy access to affordable energy is often observed to be associated with the stage of development[3, 12]. Industrialized Countries that have already achieved high living standards have recorded high per capita energy consumption, while developing Countries(LDCs) like Kenya are listed as low per capita energy consuming countries. Energy being the basic element for economic development requires due consideration to serve the purpose. Efficient utilization of available energy and improving the supply in quality and quantity are key elements in the development process today, the relationship between energy and economic growth in Kenya has become an issue of the policy makers of the Country[32]. If economic activity is to be a measure of welfare and continued growth, the implications of future energy development become central points of the debate about energy policy. Investment in wide scale intensive applications of solar technologies in developing Countries is inhibited by lack of adequate solar resource data and lack of tools to evaluate this data. Without reliable resource information, potential investors tend to avoid the risk of solar project development activities[32]. Below is a figure of a solar chimney power plant

The chimney has three main components: the solar collector, the tower or chimney, and the turbine.

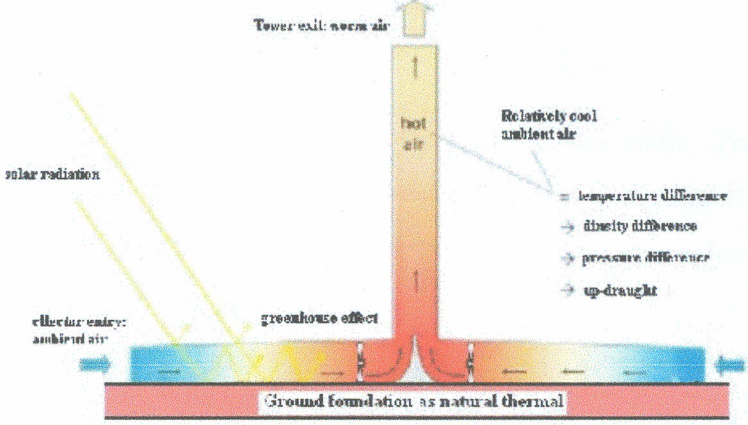

Figure 1.1: solar chimney power plant by Sharew[32]

1.1.1 Collector

It is a solar air heater, which consists of an array of interconnected short solar heat collectors. Two types of solar collectors can be used in a solar chimney: single channel with air flow between top glass and bottom absorber, the other is double channel design with single air flow between absorber and bottom covers[1]. The solar chimney uses a greenhouse-like collector which is made of glass or plastic glazing, to heat the air that drives the power plant. The collector surface gradually rises closer to the tower, to direct the heated air towards the tower, then curves up sharply at the base of the chimney in order to transmit the air flow up the chimney[15]. The collector converts solar energy to heat energy[15].

1.1.2 Chimney

The chimney (or tower) is the thermal engine of the plant. The heated air from the collector is funneled into the chimney, where the buoyancy difference between the heated air and the surrounding atmosphere creates a pressure difference that drives the air up the chimney[15]. The chimney converts the heat energy to airflow kinetic energy. The pressure difference in the tower is proportional to its height, so maximizing the height of the tower is critical to improving the efficiency of the tower[15].

1.1.3 Turbine

The solar chimney power plant uses a turbine or array of turbines to generate power. The turbine operates as cased pressure-staged generators, similar to a hydroelectric plant. It converts airflow kinetic energy to electric power. Turbines are always placed at the base of the chimney, for ease of access for maintenance and easy connection to the generating equipment. A single turbine can be mounted on vertical axes inside the chimney, while multiple turbines can be placed either in the chimney or in the transition area between the chimney and collector[15].

1.2 Basic concepts

1.2.1 Characteristics of the Solar Chimney Power plant

Apart from working on a very simple principle, solar chimneys have a number of special features

(i) The collector can use all solar radiation, both direct and diffuse. This is crucial for tropical Countries where the sky is frequently overcast.

(ii) Due to the soil under the collector working as a natural heat storage system, updraft solar chimneys can operate 24hours on pure solar energy, at reduced output at night time.

(iii) Solar chimneys are particularly reliable and not liable to break down, in comparison with other power plants. Turbines and generators- subject to a steady flow of air - are the plant's only moving parts. This simple and robust structure guarantees operation that needs little maintenance and of course no combustible fuel.

(iv) Unlike some other solar-thermal power station types, solar chimneys do not need cooling water. This is a key advantage in the many sunny Countries that already have major problems with water supply.

(v) The building materials needed for solar chimneys, mainly concrete and glass, are available everywhere in sufficient quantities. In fact, with the energy taken from the solar chimney itself and the stone and sand available in the desert, they can be reproduced on site.

(vi) solar chimneys can be built now, even in less industrially developed Countries. No investment in high-tech manufacturing plants is needed.

Even in poor Countries it is possible to build a large plant without high foreign currency expenditure by using local resources and work-force; this creates large number of jobs while significantly reducing the required capital investment and thus the cost of generating electricity.

Nevertheless, solar chimneys also have features that make them less suitable for some sites:

(i) They require large areas of flat land.

(ii) Solar chimneys are not appropriate for earthquake prone areas.

(iii) Zones with frequent sand storms are not ideal.

1.2.2 The Working Principles of a Solar Chimney Power Plant

Two basic principles behind power generation in solar updraft towers are the green house effect and buoyancy driven flow. Solar irradiation passes through the glass of the collector, is absorbed by the ground below, and re-emitted to the air under the greenhouse. Convective effects from the ground also account for some of the air heating. The high-temperature, lower density air is funneled towards the tower. The buoyancy of the air creates a pressure difference in the column of the tower, driving the air from the base of the tower to its upper outlet. The kinetic energy of the air is captured by the turbine system, which is typically located at the base of the tower[15].

A solar updraft tower converts solar radiation into electricity by combining three well-known principles: the greenhouse effect, the tower and wind turbines in a novel way. Hot air is produced by the sun under a large glass roof. Direct and diffuse solar radiation strikes the glass roof, where specific fractions of the energy are reflected, absorbed and transmitted. The quantities of these fractions depend on the solar incidence angle and optical characteristics of the glass, such as the refractive index, thickness and extinction coefficient.

The transmitted solar radiation strikes the ground surface; a part of the energy is absorbed while another part is reflected back to the roof, where it is again reflected to the ground. The multiple reflection of radiation continues, resulting in a higher fraction of energy absorbed by the ground, known as the transmittance-absorptance product of the ground. Through the mechanism of natural convection, the warm ground surface heats the adjacent air, causing it to rise. The buoyant air rises up into the chimney of the plant, thereby drawing in more air at the collector perimeter and thus initiating forced convection which heats the collector air more rapidly. Through mixed convection, the warm collector air heats the underside of the collector roof. Some of the energy absorbed by the ground surface is conducted to the cooler earth below, while radiation exchange also takes place between the warm ground surface and the cooler collector roof. In turn, via natural and forced convection, the collector roof transfers energy from its surface to the ambient air adjacent to it.

As the air flows from the collector perimeter towards the chimney its temperature increases while the velocity of the air stays approximately constant because of the increasing collector height. The heated air travels up the chimney, where it cools through the chimney walls. The chimney converts heat into kinetic energy. The pressure difference between the chimney base and ambient pressure at the outlet can be estimated from the density difference. This in turn depends upon the temperatures of the air at the inlet and at the top of the chimney. The pressure difference available to drive the turbine can be reduced by the friction loss in the chimney, the losses at the entrance and the exit kinetic energy loss. As the collector air flows across the turbine(s), the kinetic energy of the air turns the turbine blades which in turn drive the generator(s).

1.2.3 Finite difference method

The finite difference method(FDM) is the oldest among the discretization techniques for partial differential equations. Many modern numerical schemes for transport phenomena trace their origins to finite difference approximations developed in the late 1950s[7]. This method is based on local discretization of the derivative operators based on a Taylor series expansion with an assigned order of accuracy to a given point[20]. The unknowns at each grid point depend on those of the neighbouring points from the local Taylor series expansion. FDM consists of a discrete grid and a grid function. The grid is a graph of discrete grid points and a certain set of their neighbours.

Finite difference methods provide a versatile tool for the numerical solution to PDEs: their derivation in terms of divided differences is straightforward, they are easy to implement, simple to use, and they appeal to the full spectrum of linear and non-linear PDEs. However, the method is difficult for complicated geometries[7].

The typical framework of a finite difference methods is based on Cartesian grids of equispaced grid points. As a concrete example, we will consider two-dimensional spatial variables, relabelled as $(x, y)\epsilon\Omega \subset \Re_x \times \Re_y$
The domain Ω is covered with a Cartesian grid, $\Omega_\Delta = (x_j, y_k)$
A grid function, W_{jk}, $(x_j, y_k)\epsilon\Omega_\Delta$ is sought as an approximation for the corresponding point values of an exact solution w_{jk}, as $\Delta = \Delta_x + \Delta_y$ tends to zero. The grid function is obtained as the solution of an appropriate finite-difference scheme. The construction of such schemes proceeds by replacing partial derivatives with approximate divided differences. For example, one may use
$D_{+x}W_{jk} = \frac{W_{j+1,k}-W_{jk}}{\Delta_x}$, $D_{-y}W_{jk} = \frac{W_{jk}-W_{j,k-1}}{\Delta_y}$, $D_{0x}W_{jk} = \frac{W_{j+1,k}-W_{j-1,k}}{2\Delta_x}$
where D_{+x}, D_{-y}, D_{0x} are standard difference operators based on forward, backward, and centered differences respectively, which enables us to abbreviate the lengthy formulation of finite-difference schemes. There is a large variety of such difference operators to approximate first- and higher-order derivatives.
The procedure for a finite difference method follows the following steps[39]:
1. Generate a grid
2. Substitute the derivatives with some finite difference formulas at every grid points where the solution is unknown to get an algebraic system of equations.
3. Solve the system of algebraic equations to get the approximate solution at each grid point.
4. Implement and debug the computer code. Run the program to get the output.
5. Do the error analysis both analytically and numerically

1.2.4 Fundamentals of Finite Difference Methods

The Taylor series expansion is the most important in the analysis of finite difference methods. It can be written as two slightly different forms
$u(x+h) = u(x) + hu'(x) + \frac{h^2}{2}u''(x) + \cdots + \frac{h^k}{K!}u^k(x) + \cdots$
and $u(x+h) = u(x) + hu'(x) + \frac{h^2}{2}u''(x) + \cdots + \frac{h^k}{K!}u^k(\xi)$
if $|h|$ is small enough. The second one is sometimes called the extended mean value theorem.

In a finite difference method, we need to substitute the derivatives with finite difference schemes to get a linear or non-linear algebraic system. There are several different ways to substitute the derivatives with finite difference formulas.

1.2.5 Some commonly used finite difference formulas

Below we list three commonly used finite difference formulas to approximate the first order derivative of a function u(x) using the function values only.

1. The forward finite difference
$D_+u(x) = \frac{u(x+h)-u(x)}{h} = u'(x) + \frac{1}{2}u''(\xi)h$
Therefore the absolute error of the forward finite difference is proportional to h and the approximation is referred to as first order approximation.

2. The backward finite difference

$D_-u(x) = \frac{u(x)-u(x-h)}{h} = u'(x) - \frac{1}{2}u''(\xi)h$

The approximation again is a first order approximation.

3. The central finite difference

$D_0u(x) = \frac{u(x+h)-u(x-h)}{h} = 2u'(x)$

The error is proportional to h^2 and the approximation is referred to as a second order approximation.

Note that $D_0u(x) = [D_+u(x) + D_-u(x)]$

1.2.6 Approximation to high order derivatives

Usually finite difference schemes for high order derivatives can be obtained from the formulas of the lower order derivatives. We can apply the finite difference operator for the first order derivative twice to get finite difference formula for the second order derivative. For example, the central finite difference formula for second order derivative u_{xx} is

$D_0^2u(x) = D_+D_-u(x) = D_+\frac{u(x)-u(x-h)}{h} = \frac{u(x-h)-2u(x)+u(x+h)}{h^2}$

$= u_{xx}(x) + \frac{h^2}{12}u^4(\xi)$

So it is a second order approximation. The third order derivative u_{xxx} can be approximated, for example

$D^3u(x) = D_+D_0^2u(x) = \frac{u(x+2h)-3u(x+h)+3u(x)-u(x-h)}{h^3} = u_{xxx}(x) + \frac{h}{2}u^4(\xi)$

There are other approaches to constant finite difference schemes, for example the method of un-determined coefficients, polynomial interpolations and others.

The local truncation errors for the forward, backward and central finite difference are

$T_h(D_+) = f'(x) - \frac{f(x+h)-f(x)}{h} = -\frac{h}{2}f''(\xi)$

$T_h(D_-) = f'(x) - \frac{f(x)-f(x-h)}{h} = \frac{h}{2}f''(\xi)$

$T_h(D_0) = f'(x) - \frac{f(x+h)-f(x-h)}{2h} = -\frac{h^2}{6}f^4(\xi)$

In all the three cases, we have Lim $T_h = 0$ as $h \to 0$

Therefore they are all consistent.

1.3 Statement of The Problem

From the literature, Schlaich[30] recommends that power output is given by equation (2.5) and Bernardes[1] gives equation (2.4) for the calculation of power output. Both equations can only work for constant pressure driving systems. But Zhou[41] suggested that equation (2.6) can be used to give power output for both constant and non-constant pressure driving systems. He however did not attempt to investigate this. There is therefore need to determine whether equation(2.6) can be applied to give power output in a solar chimney power plant for both constant and non-constant pressure driving systems, and the effect of the driving force on the power output in the systems

1.4 Objective of The Study

The objectives of this study were to:

- determine the effect of constant and non constant pressure driving force in a solar chimney power plant.
- to assess the effect of air velocity in the chimney on the power output for constant and non constant pressure driving system.

1.5 Significance of The Study

This study is of great significance for the development of new energy resources and the commercialization of power generating systems. Since Solar chimney power plants operate using simple technology, does not require any non-renewable fuels in order to operate and has no environmental contaminations it is a cheaper option for energy, hence suitable for remote regions in developing countries and territories, especially in deserts, arid and semi-arid locations where electric power is in shortage and has extensive prospect of application. The study may also influence investment decisions by promoting alternative sources of energy in a country.

Chapter 2

LITERATURE REVIEW

Research work have been done on solar chimney power plant. In recent years more researchers have have shown interest in studying solar chimney power plant.

A model to simulate the air flow and heat transfer in solar chimney power plants was developed[27]. They evaluated the influence of a developed collective heat transfer equation, more accurate turbine inlet loss coefficient, quality collector roof glass, and various types of soil on the performance of a large scale solar chimney power plant. Results indicated that the new heat transfer equation reduces plant power output considerably, the effect of a more accurate turbine inlet loss coefficient is insignificant, while utilizing better quality glass enhances plant power production.

A compressible flow model to accurately simulate the velocity of air flow was proposed[6]. In their work, a simple mathematical model is presented which is used to evaluate the performance of the solar chimney power plant. The heat gain of air in the collector is given by;

$$c_p \dot{m} \Delta T = \eta_{coll} A_{coll} G \tag{2.1}$$

Where $c_p, \dot{m}, \Delta T, \eta_{coll}, A_{coll}$ and G are: specific heat capacity of air,mass flow rate of hot air,temperature difference,collector efficiency, cross-sectional area of collector and solar irradiance.

The mass flow rate of air passing through the chimney is calculated as

$$\dot{m} = \rho v A_c \tag{2.2}$$

Where ρ, v, A_c are: air density, airflow velocity and cross-sectional area of the chimney.

The velocity is given by

$$v = \sqrt{2gH_c\frac{\Delta T}{T_0}} \tag{2.3}$$

H is the height of the chimney and T_0 is the ambient temperature. In their findings, power production increases with increase of solar irradiance and ambient temperature.

A report on a more comprehensive analytical model in which practical correlations were used to derive equations for the airflow rate, air velocity, power output and the thermo fluid efficiency.[38]

A numerical and analytical calculations of the temperature and flow field in the upwind power plant was done[25].

A thermodynamic analysis of the solar chimney power plant and the performance of the system, which can produce electricity day and night was presented [16]. In their work, they presented a mathematical model to evaluate the relative static pressure and driving force of the solar chimney power plant system and verified the model with numerical simulations.

Later, they developed a comprehensive model to evaluate the performance of a solar chimney power plant system, in which the effects of various parameters on the relative static pressure, driving force, and efficiency have been further investigated[17]. Contrary to the results shown from ref.[25], the relative static pressure is negative and decreases along the collector but increases inside the chimney. Driving force not only depends on the chimney height but also on the solar radiation and other system dimensions.

Another numerical simulation was carried out [14] 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.

A solar chimney system was designed[2], for power production at high latitudes and evaluated its performance. Results shows that the overall thermal performance of solar chimney power plants at high latitudes is a bout 0.48 percent.

A mathematical model was also developed[26], to study the effect of various environmental conditions and geometry on the air temperature, air velocity and power output of the solar chimney[26]. Further research done, exploited the collector performance by extending the collector base and by introducing an intermediate absorber. According to them, both enhancements helped to increase the overall chimney power output. In addition, a brief economic assessment of the system costs is presented.

The potential of solar chimney for application in rural areas of developing countries was analysed[24]. Their work revealed that there exists threshold values of temperature ratios at which significant power can be produced by a solar chimney of specific dimensions. This temperature ratio has to be equal to or greater than 2.9. They disclosed that for a temperature ratio of 2.9 (the difference between the collector surface temperature and the temperature at the turbine to the difference between the air mass temperature under the roof and the collector surface temperature) 1000 W of electric power can be generated. The minimum dimension of a practical, reliable solar chimney to assist approximately fifty households in a typical rural setting was determined to be chimney length of 150 m and height above the collector of 1.5 m.

A model to estimate power output and examine the effects of some ambient conditions on the power output was developed[1]. According to ref. [1], theoretical utilizable power taken up by the turbine is expressed as

$$P = \eta_{tg} \Delta p A_c v \alpha \sqrt{1-\alpha} \tag{2.4}$$

where Δp is the pressure difference between the chimney base and its surroundings, α is the ratio of pressure drop in the turbine to pressure potential[1], η_{tg} is the efficiency of the turbine and g is the gravitational acceleration.

Another presentation on 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 was done[31].

There is a recommendation[30], that the maximum mechanical power taken up by the turbine is

$$P_{max} = \frac{2}{3} \eta_{tg} v A_c \Delta p \tag{2.5}$$

However, the two equations (1.4) and (1.5) have short comings: according to ref.[30], for equation(1.5) maximum power is achieved when two thirds of the total pressure difference is utilized by the turbine. Other computations assumed that the optimum value ranges from 0.8 to 0.9. However, in ref.[1], for equation (1.4) an optimum value of 0.97 is reported for α. Still it is indicated that the value of pressure drop which is given as 0.97 is difficult to attain[1]. Hence no unified value of the factor exists. Another point is that the optimum pressure ratio $\frac{2}{3}$ is valid only for the constant driving pressure systems where the pressure drop is constant.(ie for the constant air temperature increase in the collector). It is reported that the optimum pressure ratio is not constant during the whole day and it is dependent on the heat transfer coefficients applied to the collector[1]. It is therefore not equal to $\frac{2}{3}$. For system with non-constant driving pressure, the optimum ratio is a function of the plant size and solar heat flux.

According to Zhou[41], the electric power generated by the turbine generators, P, can be expressed as;

$$P = \eta_{tg} \Delta p v A_c \tag{2.6}$$

He suggests that this formula works for both constant and non-constant pressure driving systems.

From these short comings, there is therefore need to investigate whether equation(2.6) can be applied to give power output in a solar chimney power plant for both constant and non-constant pressure driving systems and the effect of the driving force on the power output.

The pressure difference Δp,[6] which is produced between the chimney base and the surroundings, is calculated by,

$$\Delta p = \rho_{in} g H_{sc} \frac{\Delta T}{T_0} \tag{2.7}$$

This pressure difference is called the driving pressure or the driving force inside the solar chimney power plant.

Chapter 3

RESEARCH METHODOLOGY

We relied on an analysis of mathematical equations governing fluid flow in solar chimney power plant (SCPP). Then we determined whether the equation[41] :

$$P = \eta_{tg} \Delta p v A_c$$

can be used to calculate power output in both constant and non constant driving pressure systems by first looking at the relationship between the driving force and power output in a solar chimney power plant. Partial differential equations were transformed to non-dimensionalized form then solved numerically using finite difference method under imposed thermal conditions. An implicit Crank-Nicholson scheme was used to solve continuity, momentum and energy equations. Crank-Nicholson scheme is the average of pure implicit and explicit scheme. It is unconditionally stable, convergent and accurate. The graphs for temperature and velocity distribution in the chimney plant were drawn in MATLAB software.

The pressure difference equation[6] which is given as:

$$\Delta p = \rho_{in} g H_{sc} \frac{\Delta T}{T_0}$$

is used to calculate pressure difference, which is substituted into the Power equation:

$$P = \eta_{tg} \Delta p v A_c$$

The values of other parameters in the equations above which were used in calculations of power out put, were simulated from Schlaich[31]

Also important for power generation is the wind turbine and the controlling system of the plant. Detailed analysis concerning temperature and airflow velocity inside the solar chimney were examined.

For a system with a constant driving pressure, the optimum ratio of the turbine extraction pressure to the driving pressure is assumed, while for the system with non-constant driving pressure, it is obvious that this optimum ratio is a function of the plant size and solar heat flux.

3.1 Mathematical formulation

The following mathematical equations were solved based on the assumptions that:

1. the air follows the ideal gas law.
2. only the buoyancy force is considered in solar chimney system.

3. the chimney wall is considered to be adiabatic and slippery
4. the fluid is incompressible
5. axisymmetric flow of air in the collector, i.e., nonuniform heating of the collector surface is neglected.

The basic governing differential equations that describe the flow inside the solar chimney in 2-dimension space are[19]:

Continuity equation:

$$\frac{\partial \rho}{\partial t} + \frac{\partial(\rho u)}{\partial x} + \frac{\partial(\rho v)}{\partial y} = 0 \tag{3.1}$$

Momentum equations:

$$\frac{\partial(\rho u)}{\partial t} + \frac{\partial(\rho uu)}{\partial x} + \frac{\partial(\rho vu)}{\partial y} = -\frac{\partial p}{\partial x} + \mu(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2}) \tag{3.2}$$

$$\frac{\partial(\rho v)}{\partial t} + \frac{\partial(\rho uv)}{\partial x} + \frac{\partial(\rho vv)}{\partial y} = -\frac{\partial p}{\partial y} + \mu(\frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2}) \tag{3.3}$$

$$\frac{\partial(\rho w)}{\partial t} + \frac{\partial(\rho wu)}{\partial x} + \frac{\partial(\rho wv)}{\partial y} = \rho g\beta(T - T_0) + \mu(\frac{\partial^2 w}{\partial x^2} + \frac{\partial^2 w}{\partial y^2}) \tag{3.4}$$

Energy equation:

$$\frac{\partial(\rho c_p T)}{\partial t} + \frac{\partial(\rho c_p uT)}{\partial x} + \frac{\partial(\rho c_p vT)}{\partial y} = \lambda(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2}) \tag{3.5}$$

The partial differential equations (3.1), (3.4) and (3.5) in 2-dimensions were simplified, taking density and specific heat of air as constants to give the following equations;

Continuity equation:

$$\rho\frac{\partial u}{\partial x}+\rho\frac{\partial v}{\partial y}=0$$

Dividing through by density gives:

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}=0 \tag{3.6}$$

Momentum equation:

$$\rho\frac{\partial u}{\partial t}+\rho u\frac{\partial u}{\partial x}+\rho v\frac{\partial u}{\partial y}=\mu\frac{\partial^2 u}{\partial y^2}+\rho g\beta(T-T_0)$$

Dividing through by ρ and taking $\nu=\frac{\mu}{\rho}$ we obtain:

$$\frac{\partial u}{\partial t}+u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}=\nu\frac{\partial^2 u}{\partial y^2}+g\beta(T-T_0) \tag{3.7}$$

Energy equation:

$$\rho c_\rho\frac{\partial T}{\partial t}+\rho c_\rho u\frac{\partial T}{\partial x}+\rho c_\rho v\frac{\partial T}{\partial y}=\lambda\frac{k}{\rho}\frac{\partial^2 T}{\partial y^2}$$

divide through by ρc_ρ taking $\frac{\lambda}{c_\rho}=k$ we get:

$$\frac{\partial T}{\partial t}+u\frac{\partial T}{\partial x}+v\frac{\partial T}{\partial y}=\frac{k}{\rho}\frac{\partial^2 T}{\partial y^2} \tag{3.8}$$

Since air is moving vertically along the chimney which in this case is represented by the x-axis, the second partial derivatives of u and T with respect to x in equations (3.4) and (3.5) become zero, giving equations (3.7) and (3.8) respectively.

First we transform these PDE's into non-dimensionalised form. This is because in non dimensionalised form it easier to find the solution of the equations and also to reduce the independent variables being investigated.

Let $x = LX$, $y = LG_r^{-1/4}Y$, $u = \frac{\nu}{L}G_r^{1/2}U$, $v = \frac{\nu}{L}G_r^{1/4}V$, $t = \frac{\nu}{L}G_r^{1/2}\tau$, $T = (T_h - T_0)\theta$

Where L is the characteristic length of the chimney, G_r is the Grashoff number, θ is the dimensionless temperature.

Differentiating then substituting into continuity equation (3.6),
$\frac{\partial u}{\partial x} = \frac{\nu}{L^2}G_{r^{1/2}}\frac{\partial U}{\partial X}$, $\frac{\partial v}{\partial y} = \frac{\nu}{L^2}G_{r^{1/2}}\frac{\partial V}{\partial Y}$ one finds;

$$\frac{\nu}{L^2}G_r^{1/2}\frac{\partial U}{\partial X} + \frac{\nu}{L^2}G_r^{1/2}\frac{\partial V}{\partial Y} = 0$$

since ν, L and G_r are constants, it simplifies to:

$$\frac{\partial U}{\partial X} + \frac{\partial V}{\partial Y} = 0 \tag{3.9}$$

By differentiation,
$\frac{\partial u}{\partial t} = \frac{\partial U}{\partial \tau}$,
$\frac{\partial u}{\partial y} = \frac{\nu}{L^2}G_{r^{3/4}}\frac{\partial U}{\partial Y}$,
$\frac{\partial^2 u}{\partial y^2} = \frac{\nu}{L^3}G_r\frac{\partial^2 U}{\partial Y^2}$
When we substitute partial derivatives above into momentum equation(3.7), then we simplify by dividing the equation formed by the constants $\frac{\nu^2}{L^3}G_r$

we get:

$$\frac{L^3}{\nu^2 G_r}\frac{\partial U}{\partial \tau}+U\frac{\partial U}{\partial X}+V\frac{\partial U}{\partial Y}=\frac{\partial^2 U}{\partial Y^2}+\frac{L^3}{\nu^2 G_r}g\beta(T_h-T_0)\theta \qquad (3.10)$$

In the energy equation(3.8),
$\frac{\partial T}{\partial t}=\frac{L}{\nu G_{r1/2}}(T_h-T_0)\frac{\partial \theta}{\partial \tau}$,
$u\frac{\partial T}{\partial x}=U\frac{\nu}{L^2}G_{r1/2}(T_h-T_0)\frac{\partial \theta}{\partial X}$,
$v\frac{\partial T}{\partial y}=V\frac{\nu}{L^2}G_{r1/2}(T_h-T_0)\frac{\partial \theta}{\partial Y}$,
$\frac{\partial^2 T}{\partial y^2}=\frac{G_{r1/2}}{L^2}(T_h-T_0)\frac{\partial^2 \theta}{\partial Y^2}$
we substitute these into the energy equation and simplify by dividing through by the constants
$\frac{\nu}{L^2}G_{r1/2}(T_h-T_0)$ we obtain:

$$\frac{L^3}{\nu^2 G_r}\frac{\partial \theta}{\partial \tau}+U\frac{\partial \theta}{\partial X}+V\frac{\partial \theta}{\partial Y}=\frac{1}{P_r}\frac{\partial^2 \theta}{\partial Y^2} \qquad (3.11)$$

Where P_r is the Prandtl number, $P_r=\frac{\nu \rho c_p}{\lambda}$
U and V are velocity components. Subject to the initial and boundary conditions;
$U=2, V=2, \theta=20$ at $\tau>0$,
$U=2, V=2, \theta=20$ at $X=0$
$V=2, \theta=20$ at $Y=0$
$\theta=20$
$T=T_0$ at $t\leq 0$
This is because from Xu et al.[37] the environment air velocity should not be very large ie 1-2m/s, and the temperature of the environment is set

as 293K which is equivalent to 20^0C. Equations (3.9),(3.10),(3.11) were solved subject to the above conditions by finite difference method.

In the domain of the chimney, we consider air moving horizontally at the collector base and vertically a long the chimney to the turbine. X is taken as the vertical direction and Y as the horizontal direction. We discretise the solution domain as follows;

$\Delta X = 0.1,\ 0 \leq X \leq 1.0$

$\Delta Y = 0.2, 0 \leq Y \leq 12$

$\Delta \tau = 0.00005$

With the finest grid interval and a small time step of 0.0005, stability and consistency is guaranteed. These are the sufficient conditions for convergence. A Matlab was then used to draw the graphs for temperature, velocity and power output. See appendix for the matlab codes

Computed values of temperature and velocity inside the chimney are given in table 1 below:

Table 1

Temperature distribution and airflow velocity in the chimney.

Temperature ^0C	Airflow velocity (m/s)
22	3
24	3.5
26	4
27.5	4.8
30	5
32.5	6.4
34	7
36	7.8
38	9
39	10

Since the chimney diameter is cylindrical, cross-sectional area of the chimney

$A_c = \Pi R^2 = 3.142 \times 5^2 = 78.55m^2$ where R is the radius of the chimney.

The values of temperature and velocity inside the chimney when plotted on the same axes gave figure 3.1;

Where, data1 represents airflow velocity in the chimney and data2 represents temperature distribution inside the chimney.

Some of the parameters shown in table 2 are; $\rho = 1.00kg/m^3, \eta_{tg} = 0.8$.

The driving force(pressure difference), is calculated using the temperature values in table 1, as;

$$\Delta p = \rho_{in} g H_{sc} \frac{\Delta T}{T_0}$$

for $\Delta T = 22-20 = 2, 24-20 = 4, 26-20 = 6, 27.5-20 = 7.5, 32.5-20 = 12.5, 34-20 = 14, 36-20 = 16, 38-20 = 18, 39-20 = 19$. We get,

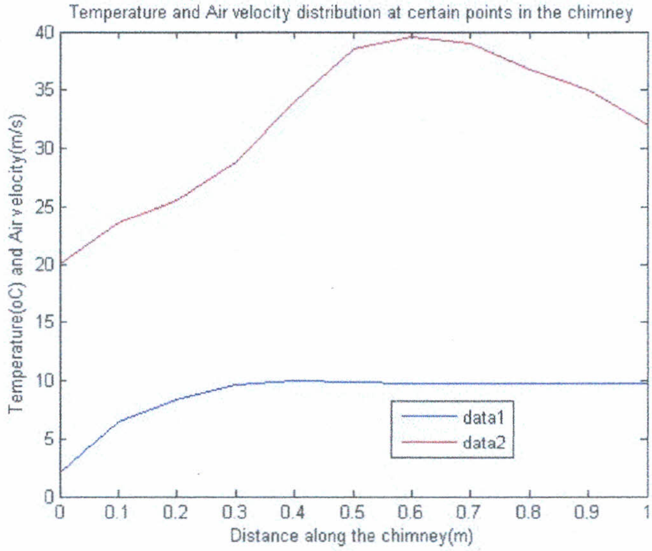

Figure 3.1: Temperature and Velocity at certain points in Solar Chimney system

$\Delta p = 1.00 \times 9.81 \times 194.6 \times \frac{2}{20} = 190.9Pa$, when the other values of t are used, we obtain; 381.8Pa, 572.7Pa, 715.9Pa, 954.5Pa, 1193.1Pa, 1336.3Pa, 1527.2Pa, 1718.1Pa, 1813Pa

For each corresponding value of velocity, we calculate power output as, $P = \eta_{tg} \Delta p v A_c$, when $v = 3$, $\Delta p = 190.9Pa$ therefore

$P = Power(P) = 0.8 \times 190.9 \times 3 \times 78.55 = 36kW$

Using other values of v and Δp, we get; 83.9kW, 144kW, 216kW, 329.9kW, 480kW, 587.8kW, 767.8kW, 971.7kW, 1139.7kW.

Some of the parameters adopted from Schlaich et al.[31] used in the calculation of the Power output are given in Table 2 below.

Table 2 Operating parameters adopted from Schlaich

Parameter(conditions)	**Value**
Chimney height	194.6m
Chimney diameter	10m
Collector diameter	244m
Collector height	2m
Solar irradiance	$263W/m^2$
air density	$1.00kg/m^3$
Efficiency of the turbine generator	0.8

Source: Schlaich et al.[31]

However, Koonsrisuk and Chitsomboon[13] proposed that for solar chimney power plants without a turbine work extraction, the maximum flow speed is achieved and the whole available driving pressure potential is used to accelerate the air flow and is thus converted completely into kinetic energy. Therefore turbine output power can be approximated from the equation,$P = \eta_{tg} \Delta p v A_c$.

The driving force Δp, affects power output because the higher the value the higher the power output. For instance, if

$\Delta p = 190.9 Pa$, $P = 36 kW$ and for $\Delta p = 1813 Pa$, $P = 1139.7 kW$.

This is for non constant driving pressure system. The optimum pressure ratio is a function of the plant size and solar heat flux. When the plant size increases, the temperature rise across the collector increases and pressure difference becomes a function of the chimney height On the other hand. For constant driving pressure system, most investigators have assumed that the optimum ratio is $\frac{2}{3}$. Computations of values by Schlaich[30] showed that the ratio is 0.82, Hedderwick[10] illustrated that the optimum ratio is between 0.66 and 0.7 during the day. Furthermore Nizetic and Klarin[23] , Schlaich et al.[31] proposed analytical approaches, and showed that the pressure ratio varied in the range of 0.8-0.9. Meanwhile Bernardes et al. reported an optimum value of 0.97. Additionally Ochieng and Onyango[24] used the ratio as $\frac{16}{27}$. Therefore, putting optimum ratio in equation (2.6) such that:

$P = \frac{17}{20} \eta_{tg} \Delta p v A_c$, where $\frac{17}{20}$ is between the recommended range of 0.8-0.9, if $\Delta p = 190.9 Pa$, $v = 3 m/s$, $P = 30.6 kW$ and if $\Delta p = 1813 Pa$, $v = 10 m/s$, $P = 968.4 kW$.

For constant driving pressure systems, the amount of plant power output can be determined by the adjustment in the turbine extraction pressure.

Chapter 4

RESULTS AND DISCUSSION

4.1 Results

Table 3: Values of temperature, velocity, pressure difference and power output

Temp.ΔT ^0C	Airflow velocity (m/s)	Pressure difference(Pa),Power output(kW)
2	3	190.9, 36
4	3.5	381.8, 83.9
6	4	572.7, 144
7.5	4.8	715.9, 216
10	5.5	954.5, 329.9
12.5	6.4	1193.1, 480
14	7	1336.3, 587.8
16	7.8	1527.2, 767.8
18	9	1718.1, 971.7
19	10	1813.6, 1139.7

Source: researcher. see pages 30,31,32.

Computed values of temperature distribution and airflow velocity inside the chimney, pressure difference using equation(2.7) and power output using equation (2.6) are given in table 3 above:

The plotted values of temperature and velocity at certain points in the chimney gave figure 4.1 and 4.2 shown below.

According to figure 4.1, temperature rises under collector into the chimney up to the maximum value, then temperature decreases. Temperature at the collector outlet is higher than the environmental temperature in the center and the entrance of the chimney. Temperature rises under

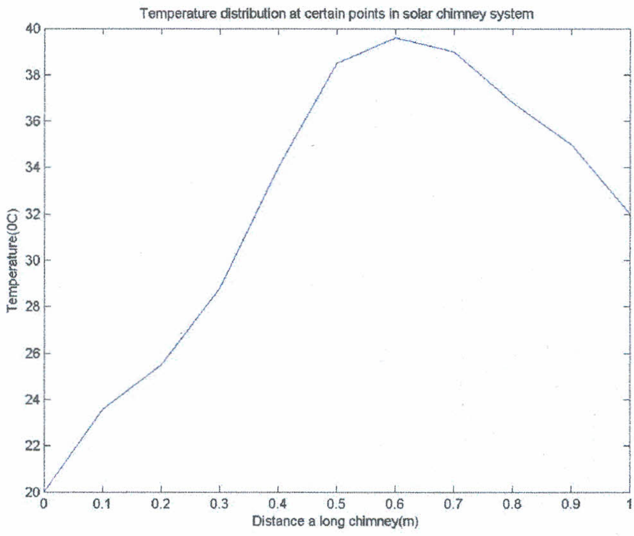

Figure 4.1: Temperature distribution at certain points in Solar Chimney system. Source: researcher.

a result of the chimney height. Therefore velocity of the flow under the roof increases along the flow path up to a point, then slightly reduces and remains constant along the tower.

When the values of the driving force(pressure difference) in the above table are plotted against power output we obtained figure 4.3 shown below. According to figure 4.3 above, the pressure difference is the driving force

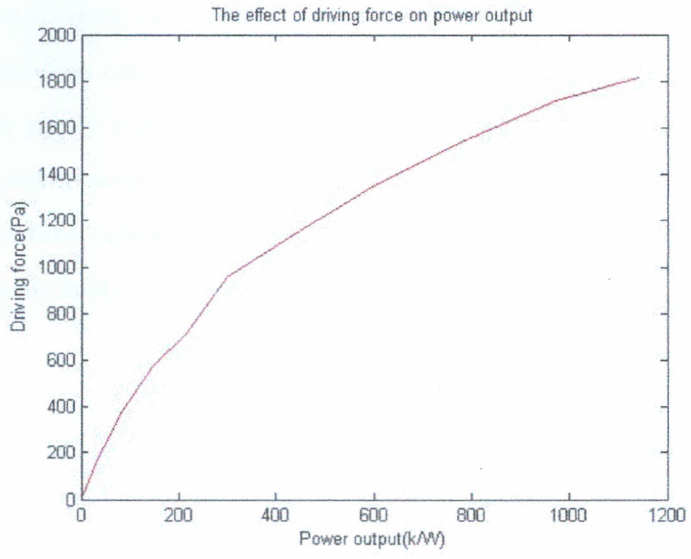

Figure 4.3: The effect of driving force on power output. Source: researcher.

which impels air to flow inside the chimney system. This driving force is the absolute value of the relative static pressure at the bottom of the chimney, which can be expressed as the product of air density, gravity, chimney height and the ratio of temperature difference to the ambient temperature. Figure 4.3 shows the influence of constant driving force on the power output in a solar chimney power plant. When soar radiation

is constant, the air temperature in the system increases which results in the decrease of the air density. Thereby, the relative static pressure in the system increases and the driving force increases accordingly and the power output increases. Similarly for non constant driving pressure system, when the solar radiation is not constant say increases, the air density will increase for the same solar chimney model, and the driving force will also increase resulting into increase in power output.
Therefore constant and non constant driving force has a direct effect on the power output of a solar chimney power plant system. Figure 4.3 shows reasonable agreement with this explanation. Power output for non constant driving pressure system can therefore be calculated using the equation:[41]

$$P = \eta_{tg} \Delta p v A_c$$

4.1.1 Calculation of Energy output for constant and non constant driving pressure systems

The power output was calculated using the formula[41]

$$P = \eta_{tg} \Delta p v A_c$$

From the results in table 3 above, the highest values of velocity, temperature and pressure in the chimney are: $v = 10m/s, \Delta T = 19^0C$,

$\Delta p = 1813.6Pa$

The other parameters shown in table 2 are; $\rho = 1.00kg/m^3, \eta_{tg} = 0.8$

Since the chimney diameter is cylindrical, Area $A_c = \Pi R^2 = 78.55m^2$

$$Power(P) = 0.8 \times 1813.6 \times 10 \times 78.55 = 1140kW$$

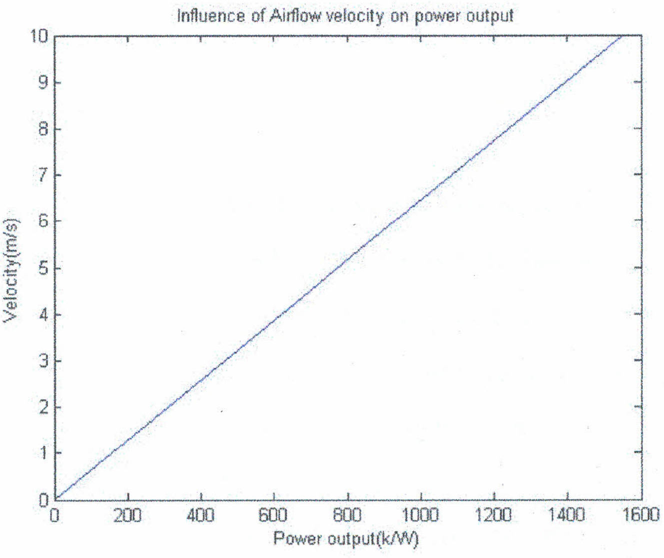

Figure 4.4: Influence of Airflow velocity on power output. Source: researcher.

4.1.2 Influence of air velocity on power output

This part addresses how air velocity affect power output in a solar chimney system. From figure 4.4, with an increase in air velocity, the power output increases.This is because when the driving force across the chimney increases, the air velocity also increases and there is an associated increase in the air mass flow rate and hence an increase in power output.

4.1.3 Validation

Solar chimney power systems on a large scale are suitable for power output at low cost. Many researchers have carried out studies on the performance of large-scale solar chimney power systems. Schlaich et al.[31] simulated the performance of a projected 200MW Solar Chimney Power plant shown in figure 4.5, which has a 27m diameter solar collector, a chimney 17.15m high and 0.8m in diameter.

In order to validate the values of temperature and velocity obtained from equations (3.6),(3.7) and (3.8), the results are compared against published data, as shown in Table 4.

Table 4 Comparison of results from the study and experimental data.

Parameter	Airflow velocity (m/s)	Temp.^0C
Simulated results by Schlaich et al.(2005)	11	18
Simulated results by Schlaich (1995)	8.1	19.5
Simulated results by Haaf et al.(1983)	15.3	7.7
Simulated results by Zhou et al.(2008)	11.5	20.7
Simulated results from the model	10	19

Figure 4.5: Solar chimney power plant by Schlaich et al.[31]

Chapter 5

CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

The results show that constant and non constant driving force affect the power output in a solar chimney power plant. An increase in the driving force causes an increase in the power output. See figure 4.3 and page 33. This is true when compared with the results from Ming et al.[18]. The power equation (2.6) can be used to determine power output in a non constant driving pressure system where there is no turbine work extraction. The maximum flow speed is achieved and the whole available driving pressure potential is used to accelerate the air flow and is thus converted completely into kinetic energy. The turbine output power can be approximated as mentioned by Koonsrisuk and Chitsomboon[13]. For constant driving pressure system the plant power output can be increased by adjusting the turbine extraction pressure. Any change in the optimum ratio affects the pressure difference and therefore affects power extraction from the turbine. This is also reported by Bernardes et al.[1]. Air velocity has a great influence on the power output of a solar chimney power plant; The increase of air velocity in the chimney increases the power production of the solar plant. While a decrease in air velocity results into a decrease in energy output.

Moreover, solar chimneys are very suitable for use in remote communities where there is high solar energy capacity; as a power source for both residential and industrial use, based on reliability, cost, and operational factors. They can provide a suitable energy source in many remote areas of a country, including areas that are not currently supplied by conventional means.

5.2 Recommendations

This study points out clearly that for constant driving pressure systems electric power is produced when part of the pressure difference is extracted by the turbine due to the heating effect. More research can be done to model an equation that can give power output for both constant and non constant pressure system. It is also explained that the driving force inside solar chimney affects power output. The amount of driving force used by the turbine is determined by optimum ratio, which many authors have assumed different values. Further research work can be done to determine the ratio which gives maximum power.

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