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Numerical and Analytical Modeling of Solar for Chimney Combined Ventilation and Power in Buildings

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Abstract- Analytical and numerical studies were carried out to investigate the performance of the combined solar chimney for power generating system and ventilation based on a developed mathematical model. Numerical solution of the problem was based on the continuity, momentum and energy equations for turbulent, steady-flow using k-ε model and the finite volume method using ANSYS Fluent CFD package. The analysis domain was a 2-D room of 4 x 4 m^2 with solar chimney of various dimension attached. The results obtained revealed that Chimney Height (CH), Collector Width (CW), Solar Heat Flux (SHF) and ambient wind speed were found to be the most important factors in the design of the SC. Results showed that the room mass flow rate increased from 1 kg/s with no wind effect to about 30 kg/s with induced wind of 1 m/s. The mass flow rate increased from about 6 to 9 kg/s at CH of 5 and 8 m respectively for no wind condition and SHF of 400 W/m^2. Power outputs were obtained for the average velocity of the chimney, collector area and chimney height. It was observed from results obtained from both the numerical and analytical analysis that power outputs of the power generating systems increases with increase in heat energy in the collector space area which is a function of the global solar radiation intensity, the collector area, and the chimney height. The power outputs results showed that with SHF of 400 W/m^2 for CH of 5 and 9 m were 33 and 85 W/m^2 respectively. The respective power output for SHF of 200 and 1,000 W/m^2 were 25 and 47 W/m^2. Furthermore, the optimum values of CH, CW and SHF were 5 m, 1 m and 417 W/m^2 respectively under no wind condition with room temperature of 300 K and chimney velocity 0.12 m/s. It was also observed that with the increase in the mass flow rate in the chimney, the ventilation requirements were adequately met.

Keywords: Solar collector; Chimney; Turbine generator; Power output, Ventilation.

I. Introduction

At the present stage of technology development fossil fuels are the main source of energy in the world. Current energy production from coal and oil is damaging to the environment and non-renewable, which necessitated the research into other sources of energy which are renewable. It is noted that inadequate energy supplies can lead to high energy costs which invariably leads to low standard of living as well as to poverty. There is therefore need for a switch to renewable sources of energy.

Renewable energy, according to Odai et al (2016) Renewable energy, is energy which comes from natural resources such as sunlight, wind, rain, tides, waves and geothermal heat, which are renewable. It is further reported according to the Renewables 2011 Global Status Report that about 16% of global final energy consumption comes from renewables, with 10% coming from traditional biomass, which is mainly used for heating, and 3.4% from hydroelectricity. New renewables (small hydro, modern biomass, wind, solar, geothermal, and biofuels) accounted for another 3% and are growing very rapidly. The share of renewables in electricity generation is around 19%, with 16% of global electricity coming from hydroelectricity and 3% from new renewables (Renewables 2011 Global Status Report).

According to current research, the use of wind power, widely used in Europe, Asia, and the United States, is increasing at an annual rate of 20%, with a worldwide installed capacity of 238,000 megawatts (MW) at the end of 2011. However, since 2004, photovoltaic passed wind as the fastest growing energy source, and since 2007 has more than doubled every two years. At the end of 2011 the photovoltaic (PV) capacity worldwide was 67,000 MW, and PV power stations are popular in Germany and Italy (Alex Morales, 2012; Renewable Energy, 2012).

Moreover, while many renewable energy projects are large-scale, renewable technologies are also suited to rural and remote areas, where energy is often crucial in human development. Climate change concerns, coupled with high oil prices, peak oil, and increasing government support, are driving increasing renewable energy legislation, incentives and commercialization in many developed and developing countries. New government spending, regulation and policies helped the industry weather the global financial crisis better than many other sectors. According to a 2011 projection by the International Energy Agency, solar power generators may produce most of the world's electricity within 50 years, dramatically reducing the emissions of greenhouse gases that harm the environment (Ben Sills, 2011; UNEP, 2007; Zhou, et al., 2007a).

Schlaich and Wolfgang (2000) in the Encyclopedia of Physical Science and Technology, Third Edition, stated that "Sensible technology for the use of solar power must be simple and reliable, accessible to the technologically less developed countries that are sunny and often have limited raw materials resources, should not need cooling water or produce waste heat and should be based on environmentally sound production from renewable materials." This is where other technology of harnessing the solar energy is sought after, that will produce the required energy at a cost lower that of the PV solar energy technology. The solar chimney meets these conditions and makes it possible to take the crucial step toward a global solar energy economy. Schlaich and Wolfgang (2000) reported that Economic appraisals based on experience and knowledge gathered so far shown that even solar chimneys rated at 100 and 200 MW are capable of generating energy at costs comparable to those of conventional power plants. This is a major reason to develop this form of solar energy utilization further. In a future energy economy, solar chimneys could thus help assure economic and environmentally appropriate utilization of energy in sunny regions.

Another application of the solar chimney is in the area of ventilation systems for buildings. Natural ventilation of buildings can be achieved with solar-driven, buoyancy-induced airflow through the solar chimney channel. Gontikaki, et al (2010) noted that the exploitation of sustainable energy sources in relations to the functional demands of buildings (for heating, ventilation, cooling, etc.) can contribute significantly to energy savings in buildings, and thus to alleviating of the present environmental, economic and social problems related to conventional energy practices. Passive (natural) ventilation of buildings is a successful means to save energy otherwise consumed for mechanical ventilation and/or cooling which can be achieved successfully with the use of a solar chimney ventilation system (Gontikaki, et al., 2010).

Background

Solar Chimney Ventilation System

Chimneys or channels are used in various applications such as heating and ventilating of buildings, drying of agricultural products, and various other passive systems such as for cooling electronic components (Bar-Cohen and Krauss, 1988; Bilgen and Michel, 1979; Ekechukwa and Norton, 1999).

A Solar Chimney (SC) ventilation system differs from a conventional chimney in that at least one wall is made transparent; solar radiation enters the chimney through the glazed part and heats up the walls. The temperature of the air inside the SC channel rises due to heat transfer from the walls and the resulting buoyancy drives the airflow through the channel. The SC pulls air from the interior of the building, which is replaced by fresh air through openings or other paths, and natural ventilation is accomplished. Performance of the SC is primarily described by the induced ventilation flow rates; in case heat harvesting is also of interest, air temperature in the channel is the other important performance indicator (Gontikaki, et al., 2010; Hirunlabh, et al., 1999; Nouanégué and Bilgen, 2009; Schlaich and Wolfgang, 2000; Sudapom and Bundit, 2006).

Burek and Habeb (2007), in their report on an experimental investigation into heat transfer and mass flow in thermosyphoning air heaters, such as solar chimneys and Trombe Walls. Their principal results showed that the mass flow rate through the channel was a function of both the heat input and the channel depth given by

$m/Q^{0:572}$ and

$m/s^{0:712}$;

And that the thermal efficiency of the system (as a solar collector) was a function of the heat input, and not dependent on the channel depth given by

$h/Q_i^{0.298}$

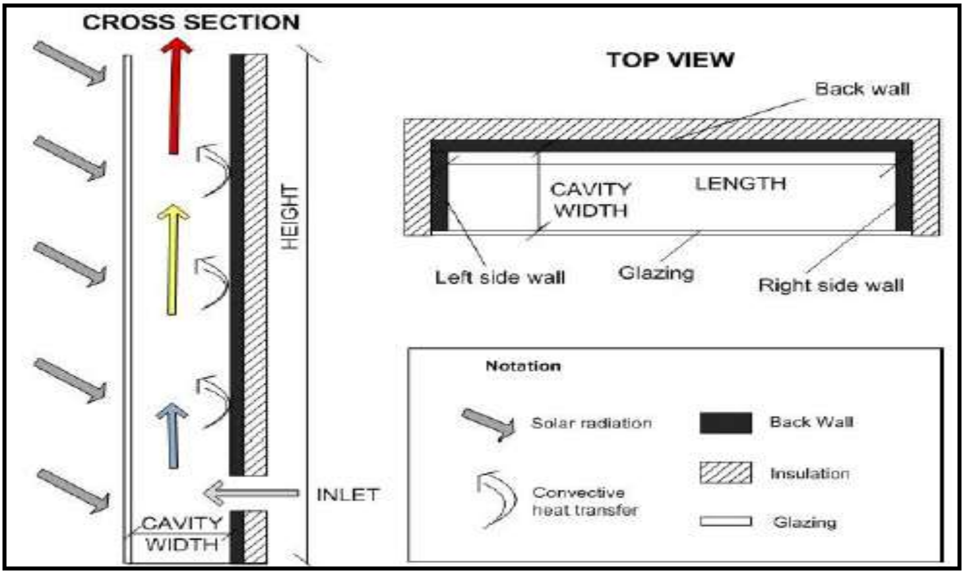

Figure 1: Cross-Section and Top View of Solar Chimney

Nouanégué and Bilgen (2009), in their Numerical study by conjugate heat transfer carried out on solar chimney systems for heating and ventilation of dwellings, produced results showing that the surface radiation modifies the flow and temperature fields, affects the Nusselt number and the volume flow rate, both in a positive way, and improves the ventilation performance of the chimneys.

Zhou et al (2007a,b) studies a combined solar house with a solar chimney and a solar water collector. Theoretical analyses were carried out to investigate natural ventilation in the solar house, compared with that in the individual chimney ventilation system under the same conditions. Their results showed that the proposed combined ventilation system improved the ventilation. When the mean solar radiation during a day from 8:00 to 18:00 h is 550 Wm^{-2}, the mean airflow rate in the combined ventilation system reaches 0-32 m/s, which is 18.5% higher than that (0.27 m/s) in the individual chimney ventilation system under the same conditions. Furthermore, results showed that the effect of night ventilation on the combined solar house is better, although less energy is drawn out from the room by comparing chimney airflow temperatures and rates when the dampers are open after 18:00 hour, with those when the dampers are open day and night.

Gontikaki et al (2010) in their report stated their parametric findings of the SC. In parametric analysis, parameters are varied to determine the sensitivity of the system's performance against each other. They stated that the most influential parameters fall under the category of geometrical (e.g. wall height, gap width), construction (e.g. type of glass, insulation) and climatic (e.g. solar radiation, wind) parameters. The effect of wall height and cavity width has in some cases been studied and expressed separately, while in others inextricably, in terms of the height-to-width aspect ratio (also referred to as height-to-gap ratio). Air flow increases with height, since the back wall's heat gains increase: in a parametric study on Trombe walls, it is reported that an increase in wall height by a quarter is equivalent to an increase in heat gains by three quarters. In another study air flow rates increased in when the wall height increased from 3.5 to 9.5m (a cavity width of 0.3m was considered). With respect to the cavity width, it was found that the induced flow rate increases with increasing width.

The intensity of solar heat flux is the motive force for the operation of the SC and is thus the most determinant factor for its performance. In the experimental study of Chen et al. (2003) varying values were considered for the uniform heat flux on the back wall and the airflow rate was found to rise by 38% for a threefold increase of heat flux (from 200W/m2 to 600W/m2). Mathur et al. (2006) found that airflow rate increases linearly with solar radiation. Based on experimental investigations on a small-scale SC, Burek and Habeb (2007) derived that the mass flow rate is proportional to $Q_i^{0.572}$ where Q_i (W/m^2) the uniform heat flux supplied to the back wall.

According to Gontikaki et al (2010) Wind is the second most influential climatic parameter, as it can create positive or negative pressures at the outlet of the SC and thus obstruct or enhance the airflow. In the outdoor experiments by Arce, et al. (2009) at a full-scale SC, the highest airflow rates coincided with the highest recorded wind velocity.

Maerefat and Haghighi (2010a), examined the heat and mass transfer characteristics of a Solar Chimney (SC) and an Evaporative Cooling Cavity using low-energy-consumption technique to improve passive cooling and natural ventilation in a solar house. The results obtained show that the system is capable of providing good indoor air condition during daytime even with low solar intensity of 200 W/m^2. Further results also show that relative humidity is a factor and at RH lower than 50%, the system performs effectively even at 40^o C. Another analysis carried out by Maerefat and Haghighi (2010b), to investigate cooling and ventilation in a solar house using solar chimney (SC) together with earth to air heat exchanger (EAHE) for passive cooling as a low-energy consuming technique for removing heat from a building in the hot seasons. The results show that the solar chimney can be used to power the underground cooling system during the daytime, without any need of electricity.

DeBlois *et al.* (2013), investigated the performance and energy level of the roof type solar chimney, and noted it being a low cost energy reduction method for passive ventilation. The results obtained indicate that the ventilated roof provided cost-free cooling and passive ventilation in all climates and seasons. The results also observed that stack effect rather than natural convection was the driving force. Further results show that the system reduced the cooling load by about 80%, while cross ventilation alone by 50% percent.

Koronaki (2013), investigated ventilation performance to assess the effectiveness of three high thermal inertia solar thermosyphonic configurations, used as night natural ventilation systems. The results obtained show that a thermal chimney with duct attached behind the absorber facing West was the most effective design with predicted flow rate 98% higher than the a similar size conventional SC.

Solar Chimney Power Plant

Man learned to make active use of solar energy at a very early stage: greenhouses helped to grow food, chimney suction ventilated and cooled buildings and windmills ground corn and pumped water. Schlaich and Wolfgang (2000) stated the solar chimney's three essential elements - glass roof collector, chimney, and wind turbines - have thus been familiar from time immemorial. A solar-thermal chimney power plant simply combines them in a new. The technology combines three components: a collector, a chimney and turbines. In the collector, solar radiation is used to heat an absorber (ordinarily soil or water bags) on the ground, and then a large body of air, heated by the absorber, rises up the chimney, due to the density difference of air between the chimney base and the surroundings. The rising air drives large turbines installed at the chimney base to generate electricity. The concept of solar chimney power technology was first conceived many years ago first described in a publication written by a German author, Gunther in 1931 (Zhou, *et al*, 2010), again presented in 1978 and proven with the operation of a pilot 50 kW power plant in Manzanares, Spain in the early 1980s (Pretorius & Kröger, 2006; Liu, *et al.*, 2005; Schlaich and Wolfgang, 2000; Zhou, *et al.*, 2010).

Pretorius and Kröger (2006) examined the effect of a convective 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. The Results show that the new heat transfer equation reduces plant power output considerably. Further results show that the effect of a more accurate turbine inlet loss coefficient is trivial, and using better quality glass enhances plant power production. It was also discovered that using Limestone and Sandstone soil produced similar results to Granite.

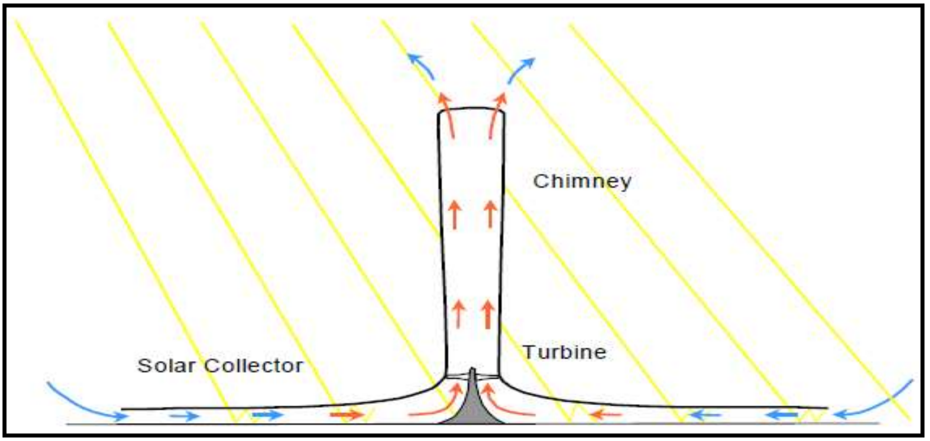

Figure 2: Principle of the solar chimney: glass roof collector, chimney tube, wind turbines

Fluri and von Backstrom (2008a) carried out performance evaluation using analytical models and optimisation techniques on several turbo-generator layouts of SCPP. Results show that slight changes in modelling approach have significant impact on the performance estimate. Further results conclude that the single rotor layout without guide vanes performs very poorly. The counter rotating layouts provide the highest peak efficiencies, however at relatively low speeds, which leads to undesirable higher torque for the same power output. Further study by Fluri and Von Backstrom (2008b) investigated the performance of the Power Conversion Unit of a SCPP and its effect on the plant. The results obtained show that single vertical axis turbine has a little better efficiency and energy yield due to some loss mechanisms are not present, however, the output torque value makes its feasibility less desirable. Further results show that redesigning the flow passage reduces aerodynamic losses and improve performance. Results show that the PCU efficiency depreciates significantly with increasing diffuser area ratio but improves only slightly with reducing the diffuser area ratio below unity.

Zhou et al (2009) in their report found that the results based on the Manzanares prototype show that as standard lapse rate of atmospheric temperature is used, the maximum power output of 102.2 kW is obtained for the optimal chimney height of 615 m, which is lower than the maximum chimney height with a power output of 92.3 kW. Sensitivity analyses are also performed to examine the influence of various lapse rates of atmospheric temperatures and collector radii on maximum height of chimney. The results show that maximum height gradually increases with the lapse rate increasing and go to infinity at a value of around 0.0098 $K\ m^{-1}$, and that the maximum height for convection and optimal height for maximum power output increase with larger collector radius.

Pretorius and Krögerb (2009) in their report presented results indicating that windy conditions impair plant performance considerably, while nocturnal temperature inversions cause significant reductions in night-time output. Petela (2009), carried out a thermodynamic analysis of energy and exergy balances on a simplified model of solar chimney power plant (SCPP). The results obtained show that an energy input of 36.81 MW of solar radiation to SCPP, corresponds to 32.41 MW input of radiation exergy.

Proposed combined ventilation and power solar chimney

Zhou et al (2009) describes solar chimney power technology, designed to produce electric power on a large-scale, as utilizing solar energy to produce ventilation that drives wind turbines to produce electric power. The generation of power in the process of passive ventilation is the main objective of the study; the development of a combined ventilation and power solar chimney.

II. Mathematical Model

Zhou et al (2007b) in their study developed a mathematical model based on energy balance to predict the performance of the solar chimney thermal power generating equipment for different conditions. The following assumptions are made:

1. Air follows the ideal gas law.
2. The mathematical model is considered to be in steady state.
3. There is no friction or leakage considered in the system.
4. Only the buoyancy force is considered, and wind-induced natural ventilation in the ambient is not included.
5. The temperature of the natural ground under the heat insulator bed is equal to that of the ambient.

Figure 2 shows the physical model for the solar chimney thermal power generating system. The absorber and the glazing can be heated to temperatures of T_a and T_p, respectively, due to solar energy and the greenhouse effect produced in the solar collector. Air at the ambient temperature T_∞ enters into the collector and is heated to the mean temperature T_f in the solar collector. The energy balance equations for the different components of the system are given as follows:

Collector and Chimney Glazing:

$$S_1 + h_{rap}(T_a - T_p) + h_p(T_p - T_f) = U_t(T_p - T_\infty) \quad (1)$$

where, S_1 denotes solar radiation absorbed by glazing cover;

h_{rap} is the radiation heat transfer coefficient between absorber and glazing cover; h_p is the convective heat transfer coefficient between glazing cover and airflow in the solar collector;

U_t denotes the overall heat loss coefficient from glazing cover to ambient, including convection by wind, radiation heat transfer from glazing cover to sky and conduction through glazing.

Absorber:

$$S_2 = h_a(T_a - T_f) + h_{rap}(T_a - T_p) + U_b(T_a - T_\infty) \quad (2)$$

where, S_2 denotes solar radiation absorbed by absorber;

h_a is the convective heat transfer coefficient between absorber bed and airflow in the solar collector;

U_b denotes the overall heat transfer coefficient from the absorber to the earth.

Collector airflow:

$$h_a(T_a - T_p)A_{coll} = h_p(T_p - T_f)A_{coll} + \dot{Q} \quad (3)$$

where, A_{coll} is the collector area;

Q denotes the useful heat energy transferred to the moving airflow by convection.

The mean temperature of hot air, T_f , can be given by,

$$T_f = \varepsilon T_\infty + (1 - \varepsilon) T_0 \quad (4)$$

where, T_o is the collector outlet airflow temperature;

ε denotes the constant in mean temperature approximation, which is recommended as 0.25 by Hirunlabh et al. (1999),

$$\dot{Q} = c_p \dot{m}(T_0 - T_\infty) = c_p \dot{m}\left(T_f - T_\infty\right)/(1 - \varepsilon) \quad (5)$$

where, c_p is the specific heat of air; m denotes the mass flow rate of hot airflow in the solar collector, which is equal to the mass flow rate of hot airflow passing through the solar collector outlet and can be calculated by the following equation,

$$\dot{m} = \rho A_{ch} V \quad (6)$$

where ρ is the air density at the solar collector outlet;

A_{ch} is the cross-sectional area of solar chimney;

V denotes hot air velocity at the solar collector outlet.

According to Schlaich J. (1995), V can be expressed as

$$V = \sqrt{2gH_{ch}(T_0 - T_\infty)/T\infty} \quad (7)$$

where g is the acceleration due to gravity and

H_{ch} is the height of the chimney.

System's Power:

Power output P_{out} can be found as (Schlaich, 1995),

$$P_{out} = \frac{1}{3}\eta_w \rho A_{ch} V^3 \quad (8)$$

where $ή_w$ is the turbine generator efficiency, usually between 50% and 90%.

Ortega (2011) stated in the analyses of solar chimney design, that the Boussinesq Model treats density as constant value in all the equations except in the buoyancy term of the momentum equation, given as follows

□ = □0 1 − □Δ□ → □Δ□ ≪ 1 (9)

Δ□□□□□□□□□□ = □□□□Δ□

(10)

Chimney

Assuming a uniform velocity and temperature inside the chimney the theoretical flow rate will be (Ortega, 2011):

- Energy balance in the chimney

$$Q = q\rho c_p T_{out} - T_{ext} \quad (11)$$

$$T_{out} = T_{ext} + \frac{Q}{q\rho c_p} \quad (12)$$

- Approximation velocity profile constant

$$V \cdot A = q \quad (13)$$

- Drag coefficient Vs constant pressure loss

$$C_d = \frac{1}{\sqrt{\sum K_{loss}}} \quad (14)$$

- Bernoulli equation

$$\rho g H \frac{(T_{out} - T_{ext})}{T_{ext}} = \frac{1}{2}\rho V^2 \sum K_{loss}$$

$$\rho g H (T_{out} - T_{ext}) = \frac{1}{2}\rho T_{out}\left(\frac{q}{A c_d}\right)^2$$

$$q^3 + q^2 \frac{Q}{T_{ext}\rho c_p} - \frac{(A C_d)^2 2gHQ}{T_{ext}\rho c_p} = 0 \quad (15)$$

The value of C_d is calculated as a function of the sum of coefficient of pressure loss of the inlet, the nozzle, the outlet and the friction of the walls

$$\sum K = K_{inlet} + K_{nozz} + K_{outlet} + f\frac{H}{Dh} \quad (16)$$

In theory, C_d is a function of the flow rate, because the factor *f* depends of the Reynolds's number Re, but □ ∈ 0.04, 0.015 which gives a □□ ∈ 0.75, 0.788, which is small difference (Ortega, 2011). Therefore C_d can be considered only as the function of the height:

$$\sum K = 0.04 + 0.48 + 1 + 0.04\frac{H}{0.5} \quad (17)$$

$$C_d = \frac{1}{\sqrt{1.52+0.08H}} \quad (18)$$

Natural ventilation takes place when buoyancy pressure overcomes the sum of all flow pressure losses. A mathematical model based on Bernoulli's equation is used to evaluate the system flow rate (Maerefat & Haghighi, 2010a). The chimney net draft is given by the following formula

$$Draft_{ch} = (\rho_a - \rho_{chout})gH - \left(\sum c_j + \zeta_{ch}\frac{L_{ch}}{(d_{hyd})_{ch}}\right) \times \left(\frac{\rho_{chout}V_{ch}^2}{2}\right) \quad (19)$$

where, c_j is the pressure loss coefficients,

ζ_{ch} is the chimney friction factor,

V_{ch} is the chimney air velocity,

ρ_{chout} is the air density at chimney outlet,

ρ_a is the ambient air density.

The kinetic energy efficiency is one of the solar chimney properties that allow the comparison of the solar chimney with other technologies. This efficiency can be calculated as the coefficient between the kinetic energy and the power generated in the solar collector:

$$\eta = \frac{\frac{1}{2}\dot{m}V^2}{Q} = \frac{\frac{1}{2}q\rho\left(\frac{q}{A}\right)^2}{Q}$$

$$\eta = \frac{q^3\rho}{2QA^2} \quad (20)$$

Computational Fluid Dynamics (CFD) Analysis

The CFD analysis of this study is performed using ANSYS FLUENT software (ANSYS, 2011). The mathematical model for the CFD analysis are the Navier-Stokes equations, the Continuity and momentum equations and the energy equation for the heat transfer analysis of the system. Additional transport equations are modelled for turbulent flow. In Reynolds averaging, the solution variables in the instantaneous (exact) Navier-Stokes equations are decomposed into the mean (ensemble-averaged or time-averaged) and fluctuating components. For the velocity components:

$$u_i = \hat{u}_i + u_i' \quad (21)$$

where $\hat{u}_i$ and u_i' are the mean and fluctuating velocity components (j = 1,2,3). Likewise, for pressure and other scalar quantities:

$$\phi = \hat{\phi}_i + \phi' \quad (22)$$

where ϕ denotes a scalar quantity. Substituting expressions of this form for the flow variables into the instantaneous continuity and momentum equations and taking a time average yields the ensemble-averaged momentum equations, written in Cartesian tensor form as:

$$\frac{\partial\rho}{\partial t} + \frac{\partial}{\partial x_i}(\rho u_i) = 0 \quad (23)$$

$$\frac{\partial}{\partial t}(\rho u_i) + \frac{\partial}{\partial x_j}(\rho u_i u_j) = -\frac{\partial}{\partial x_i} + \frac{\partial}{\partial x_j}\left[\mu\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} - \frac{2}{3}\delta_{ij}\frac{\partial u_l}{\partial x_l}\right)\right] \quad (24)$$

Equation (23) and Equation (24) are the Reynolds-averaged Navier-Stokes (RANS) equations and have the same general form as the instantaneous Navier-Stokes equations, with the velocities and other solution variables now representing ensemble-averaged (or time-averaged) values. Additional terms now appear that represent the effects of turbulence. Reynolds stresses $(-\rho\overline{u_i'u_j'})$ are modeled in order to close Equation 24. The Boussinesq hypothesis is related to the Reynolds stresses to the mean velocity gradients:

$$-\rho\overline{u_i'u_j'} = \mu_t\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right) - \frac{2}{3}\left(\rho k + \mu_t\frac{\partial u_k}{\partial x_k}\right)\delta_{ij} \quad (25)$$

The Boussinesq hypothesis is used in the $k - \mathcal{E}$ models employed in the study. The standard $k - \mathcal{E}$ model is based on model transport equations for the turbulence kinetic energy (k) and its dissipation rate ($\mathcal{E}$).

$$\frac{\partial}{\partial t}(\rho k) + \frac{\partial}{\partial x_i}(\rho k u_i) = \frac{\partial}{\partial x_j}\left(\left(\mu + \frac{\mu_t}{\sigma_k}\right)\frac{\partial k}{\partial x_j}\right) + G_k + G_b - \rho\varepsilon + S_k \quad (26)$$

$$\frac{\partial}{\partial t}(\rho\varepsilon) + \frac{\partial}{\partial x_i}(\rho\varepsilon u_i) = \frac{\partial}{\partial x_j}\left(\left(\mu + \frac{\mu_t}{\sigma_\varepsilon}\right)\frac{\partial \varepsilon}{\partial x_j}\right) + C_{1\varepsilon}(G_k + C_{3\varepsilon}G_b) - C_{2\varepsilon}\rho\frac{\varepsilon^2}{k} + S_\varepsilon \quad (27)$$

In the equations above, G_k represents the generation of turbulence kinetic energy due to the mean velocity gradients, and G_b is the generation of turbulence kinetic energy due to buoyancy. ANSYS FLUENT solves the energy equation in the following form:

$$\frac{\partial}{\partial t}(\rho E) + \nabla\cdot\left(\bar{V}(\rho E + \rho)\right) = \nabla\cdot\left(k_{eff}\nabla T - \sum_j h_j\bar{J}_j + \left(\bar{\tau}_{eff}\cdot\bar{V}\right)\right) + S_h \quad (28)$$

Where k_{eff} is the effective conductivity (k + k_t, where k_t is the turbulent thermal conductivity, defined according to the turbulence model being used), and $\bar{J}_j$ is the diffusion flux of species j. The first three terms on the right-hand side of Equation (8) represent energy transfer due to conduction, species diffusion, and viscous dissipation, respectively.

Computational Domain

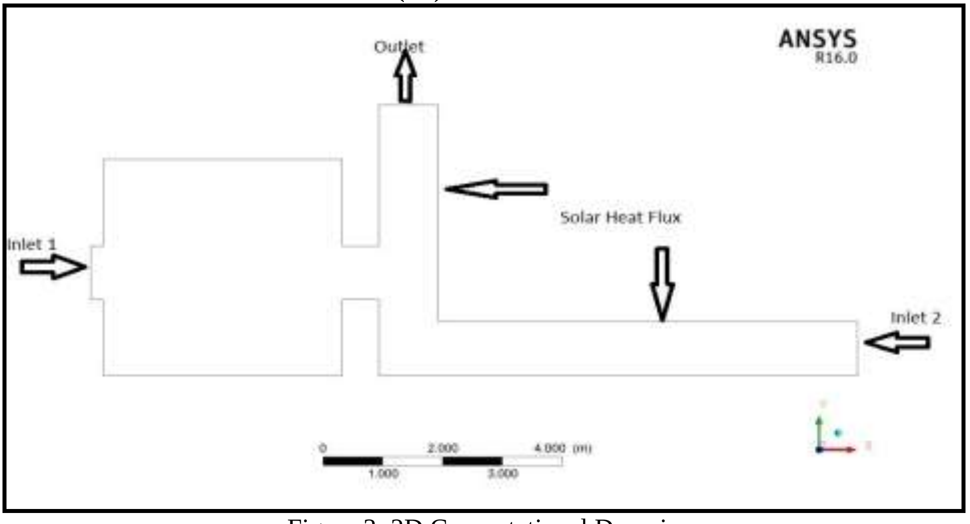

Figure 3: 2D Computational Domain

III. Results and Discussion

The analytical model was simulated using an Excel Spread Sheet, while the numerical simulation was carried out using ANSYS Fluent package. The power outputs simulated by the program are obtained for different conditions, as shown in Figures 15 and 16. The results show that power outputs of the power generating systems increases with increase in the Heat Energy in the collector space area which is a function of the global solar radiation intensity and collector area, and chimney height.

Analytical Results:

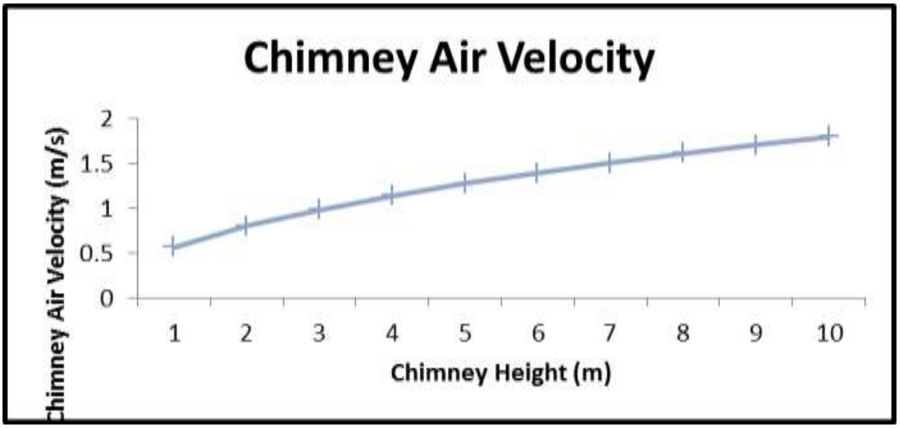

Figure 4: Effect of Chimney Height on Chimney Air Velocity (Analytical)

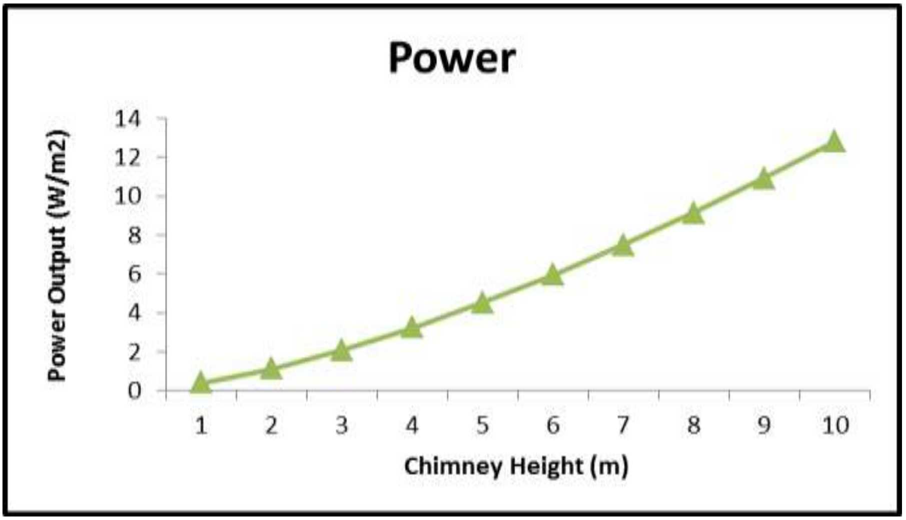

Figure 5: Effect of Chimney Height on Power Generated

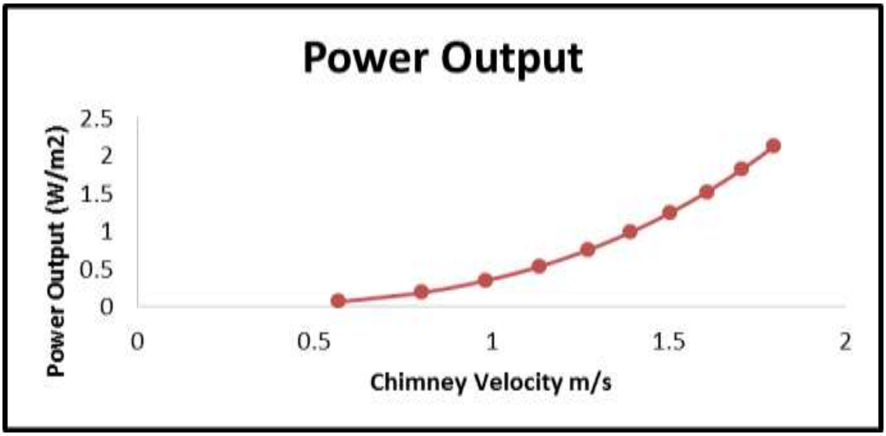

Figure 6: Effect of Chimney Air Velocity Power Output Ra = 10^{10}

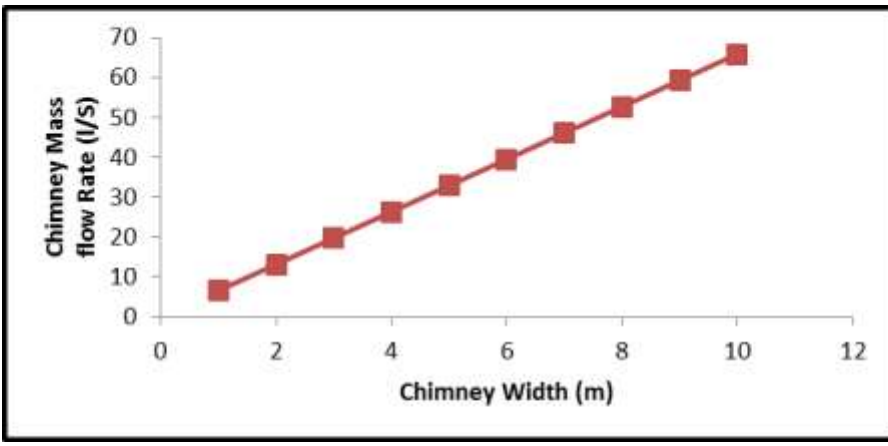

Figure 7: Effect of Chimney Width on Air Mass Flow Rate

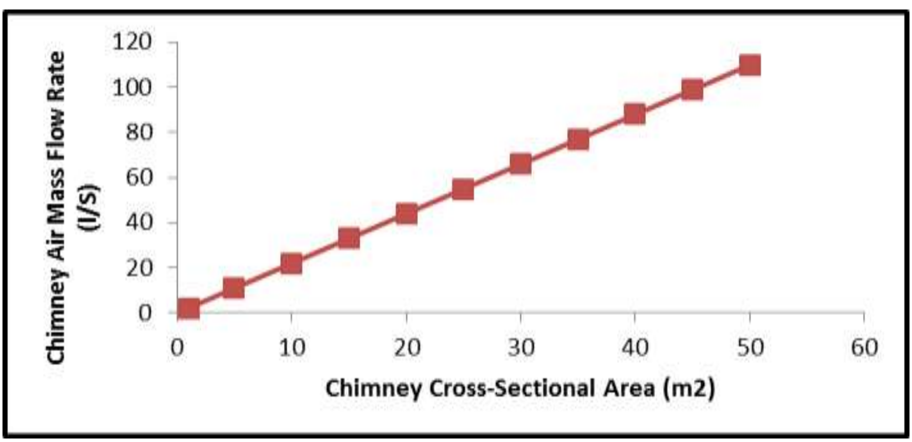

Figure 8: Effect of Chimney X-Sectional Area on Air Mass Flow Rate

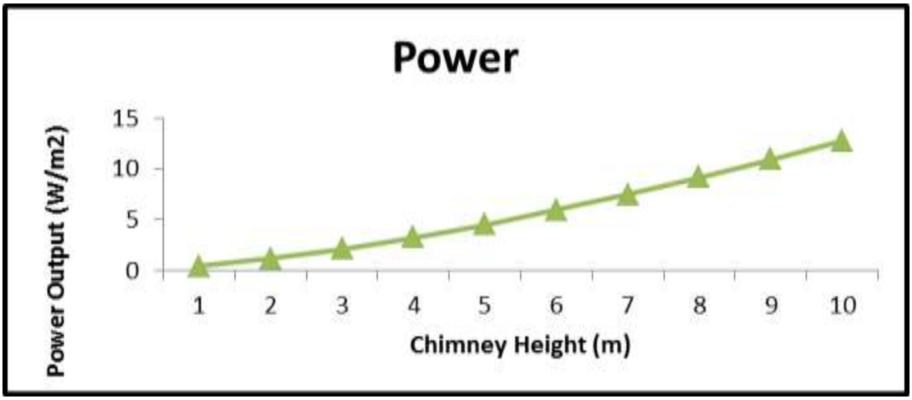

Figure 9: Effect of Chimney Height on Power Generated

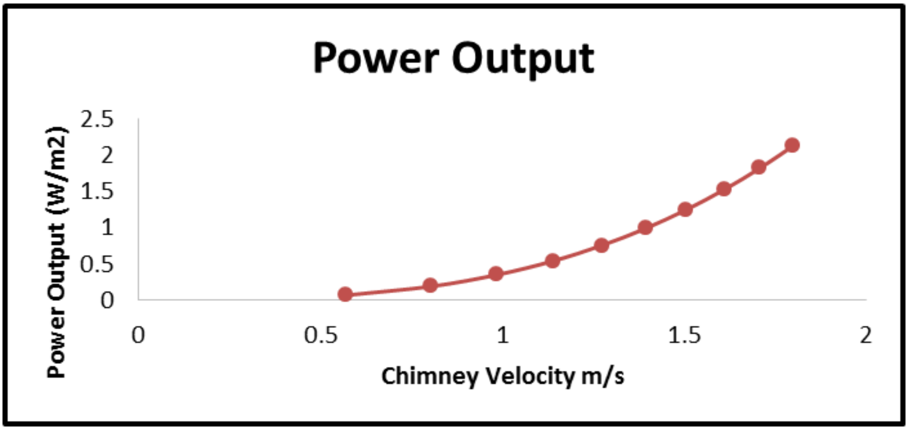

Figure 10: Effect of Chimney Air Velocity Power Output Ra = 10^{10}

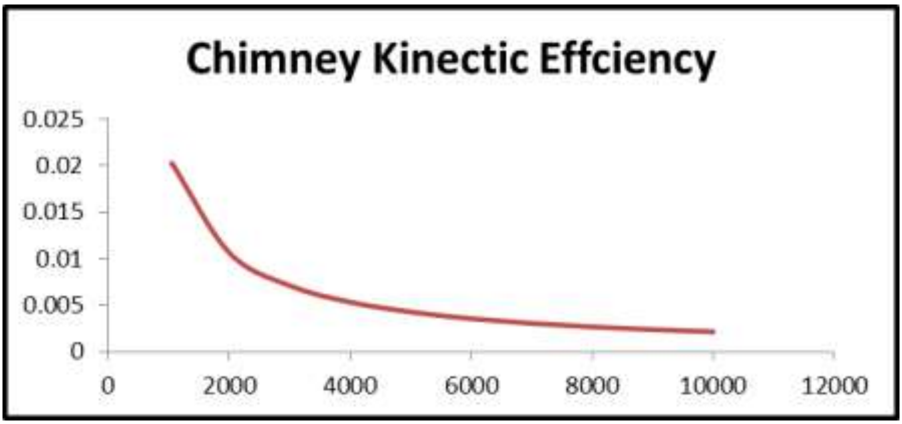

Figure 11: Comparison of Heat Energy (Power Generated) in the Collector with Chimney Kinetic Efficiency

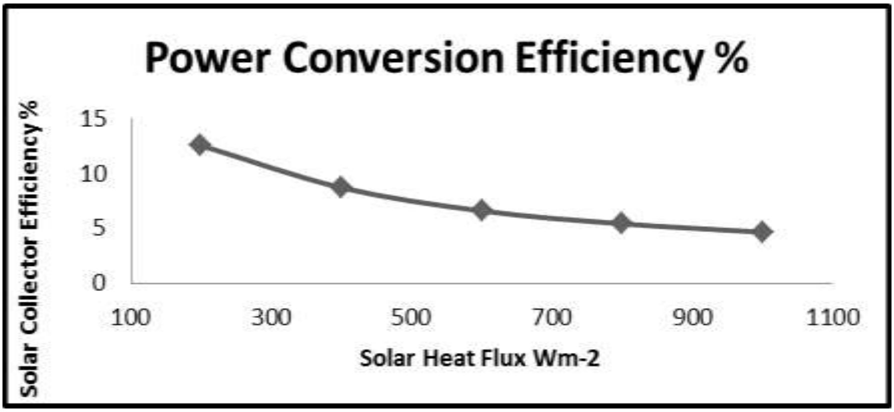

Figure 12: Solar Collector Efficiency with Increase in Solar Heat Flux

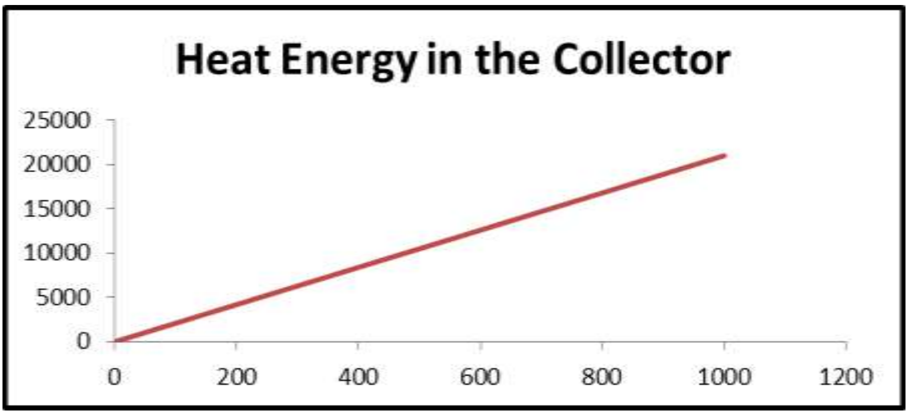

Figure 13: Effect of Collector Area on Heat Energy in the Collector Space

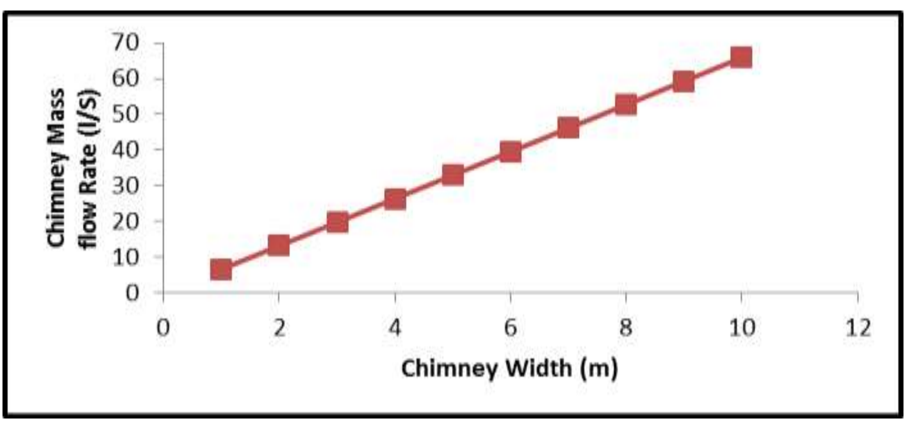

Figure 14: Effect of Chimney Width on Air Mass Flow Rate

Numerical Results:

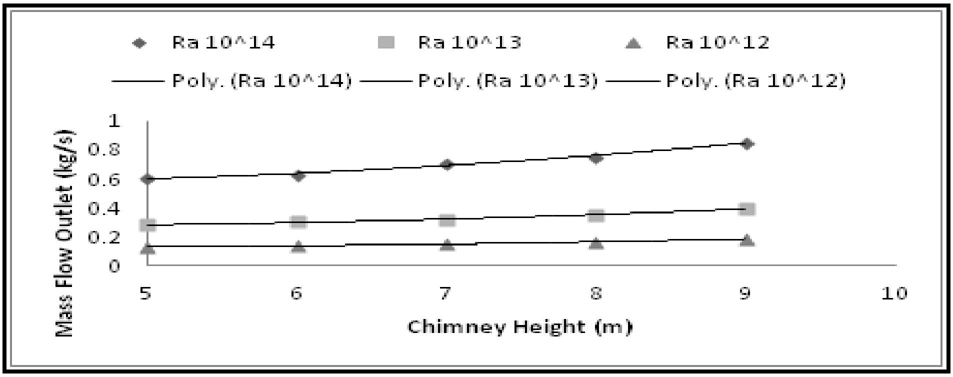

Figure 15: Effect of Chimney Height on Mass Flow at Outlet at no Induced Wind, CH of 5 m and SHF of 400 W/m^2 Condition for Ra = 10^{12} – 10^{14}

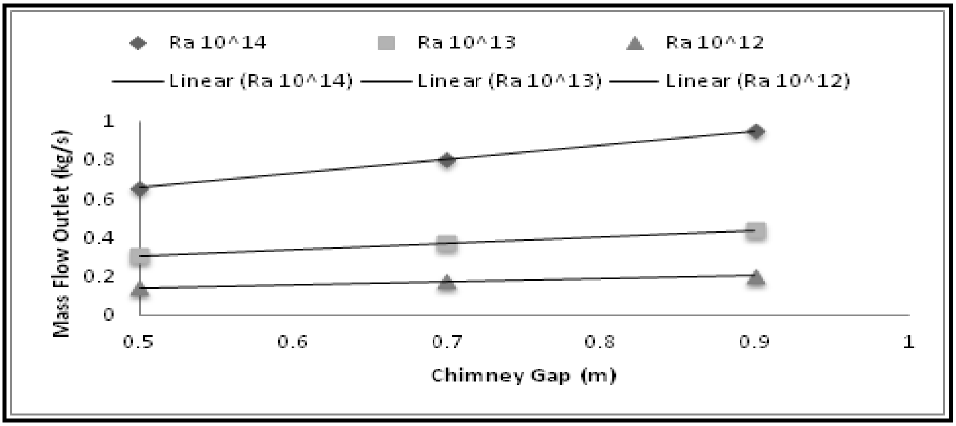

Figure 16: Effect of Chimney Gap on Mass Flow at Outlet at no Induced Wind, CH of 5 m and SHF of 400 W/m^2 Condition for Ra = 10^{12} – 10^{14}

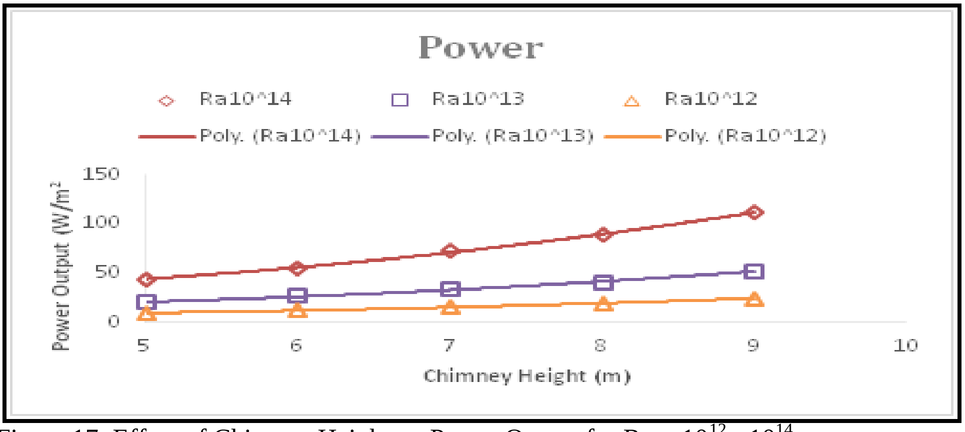

Figure 17: Effect of Chimney Height on Power Output for Ra = 10^{12} - 10^{14}

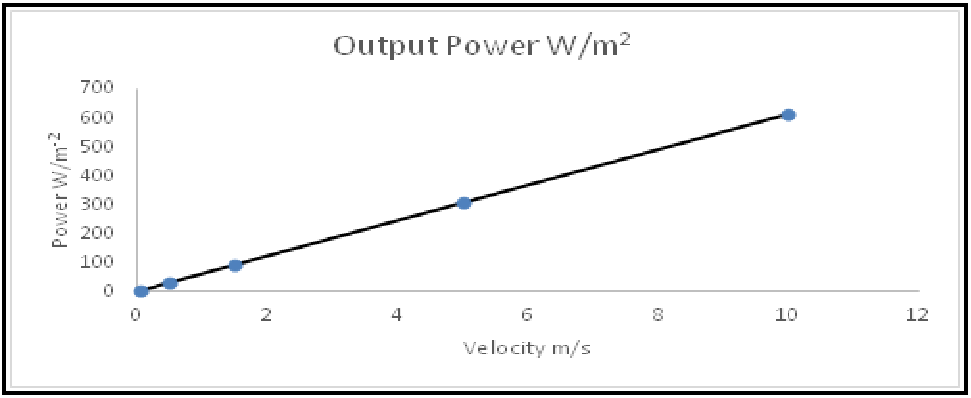

Figure 18: Effect of Flow Velocity on Power Output Ra = 10^{14}

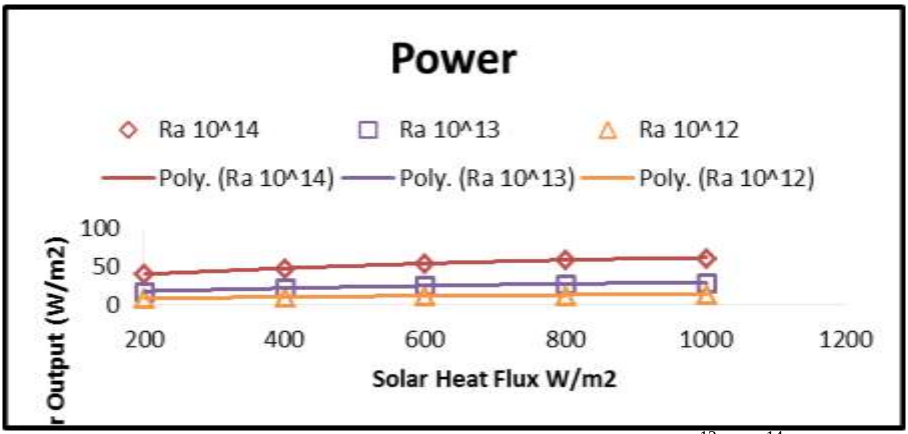

Figure 19: Effect of Solar Heat Flux on Power Output for Ra = 10^{12} - 10^{14}

Effect of Solar Heat Flux, Chimney Height and Chimney width on Outlet Mass Flow Rate and Chimney Velocity

The outlet mass flow rate, which is also a function of the chimney velocity was observed to increase from 0.5 to 0.8 kg/s at Ra = 10^{14} for SHF of 200 to 1 000 W/m^2 with a chimney height of 5 m and width of 1 m. The velocity increased from about 0.6 to about 2 m/s for chimney height of 1 m to 10 m. This confirms observations from literature that the chimney height is a major factor in determining the power output of the SC (Schlaich and Schiel, 2000; Liu *et al*, 2005; Pretorius and Kröger, 2006; Zhou *et al*, 2009).

Effect of Solar Heat Flux and Chimney Height on Power Output

The power output per unit area was found to increase from 39 to 61 W/m^2 for solar radiation of 200 and 1,000 W/m^2 at Ra = 10^{14}, with a solar radiation to flow power conversion of 19.5 % and 6.1 % respectively. The effect of the chimney height on the power output of the SC was 154.6 % increase from power output of 44 to 112 W/m^2 at chimney height of 5 to 9 m at solar radiation of 400 W/m^2 and Ra = 10^{14}. The conversion effect (ratio of power to chimney height) are 8.8 and 12.4 for heights of 5 and 9 m respectively.

Effect of Flow Velocity on Power Output

The flow velocity is another major factors of the power output of the SC. Results show that an increase in channel velocity from 0.05 to 1.5 m/s caused the power output to increase from 3.1 to 92.1 W/m^2, while an increase to 5 and 10 m/s resulted in a power output of 307.1 and 614.1 W/m^2 respectively. It was noted that the channel velocity was affected by factors, which include the ambient wind velocity, the temperature difference between the ambient temperature and the channel temperature (which was a function of the solar heat flux) and the geometry of the SC. However, the factor within human control was the geometry of the system. At constant ambient conditions, it is suggested that a convergent divergent channel may help in increasing the velocity at required points for an increase in power output instead of the rectangular channel used.

Optimised Model Analysis

The optimisation criteria have been set with model constraints that will produce optimum effect for both room ventilation and power generation. Two (2) optimal solutions were found that placed the chimney height and the solar collector breadth at values of 5 m and 1 m respectively. This solution minimised the chimney height and the solar collector breadth, which will reduce the size of the system and consequently reduce the cost of the system.

The minimisation of the solar heat flux was between 200 and 600 W/m^2, as a result of the average solar insolation experienced in the Southern Nigeria Region. The optimised solutions found for the solar heat flux for the two optimum (2) solutions are 407 and 417 W/m^2 which is close to the average range of Solar Heat Flux values for Nigeria (Osueke *et al*., 2013).

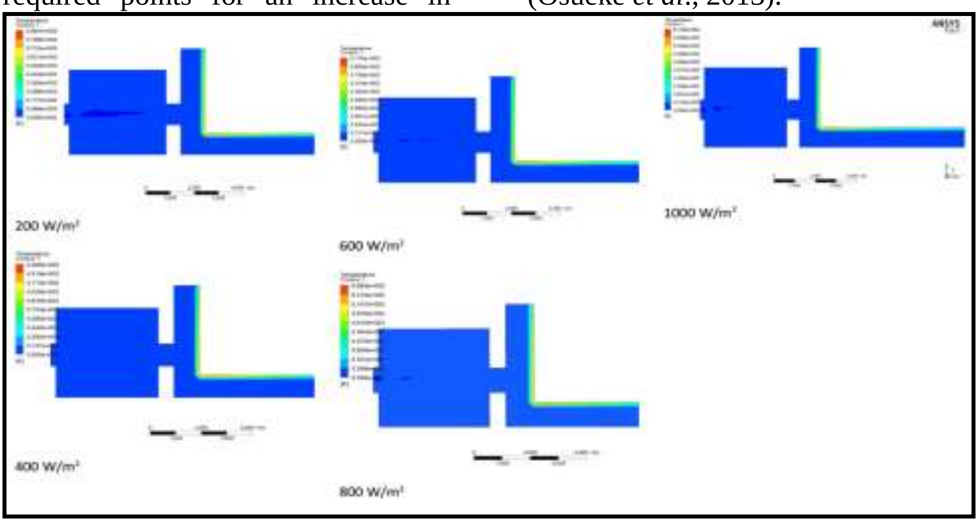

Figure 20: The temperature contour of the SC system at heat flux of 200 – 1,000 W/m^2

The results from the optimised model showed that the room temperature was conserved and maintained at the value of 300 K (Figure 20). This increase in velocity at the cavity as the room air enters the chimney is due to the boundary layer effect at the cavity and the suction pressure differential; coupled with the stack effect within the chimney, the velocity increase was observed within the chimney from 0.05 m/s to 0.12 m/s.. The chimney temperature was found to have increased from 300 K to 314.7 K and 315.1 K for both solutions.

The velocity at the junction between the chimney and the horizontal solar collector also showed an increase in velocity from 0.05 m/s to 0.07 m/s for both optimised solutions. However, it was observed that for power generation it will be more desirable to put the turbine at a position close to the top of the Chimney, since it is this part that correspond to maximum velocity.

Moreover, Gontikaki *et al.* (2010) noted that wind is a highly influential climatic parameter and its effect is a major contributor to the effectiveness of a SC system: In that respect, thus would improve the results from the optimised model.

Effect of Solar Radiation on Ventilation flow pattern and Temperature within the Room

The outlet mass flow rate, which is also a function of the chimney velocity was observed to increase from 0.5 to 0.8 kg/s at Ra = 10^{14} for SHF of 200 to 1 000 W/m^2 with a chimney height of 5 m and width of 1 m. The flow within the room showed that with cross ventilation the flow across increases in velocity as the solar radiation increases, creating two pressure zones above and one below the cross flow section (Figure 21). This is due to the pressure differential created by the cross flow and the temperature vis-à-vis density of air at the two zones.

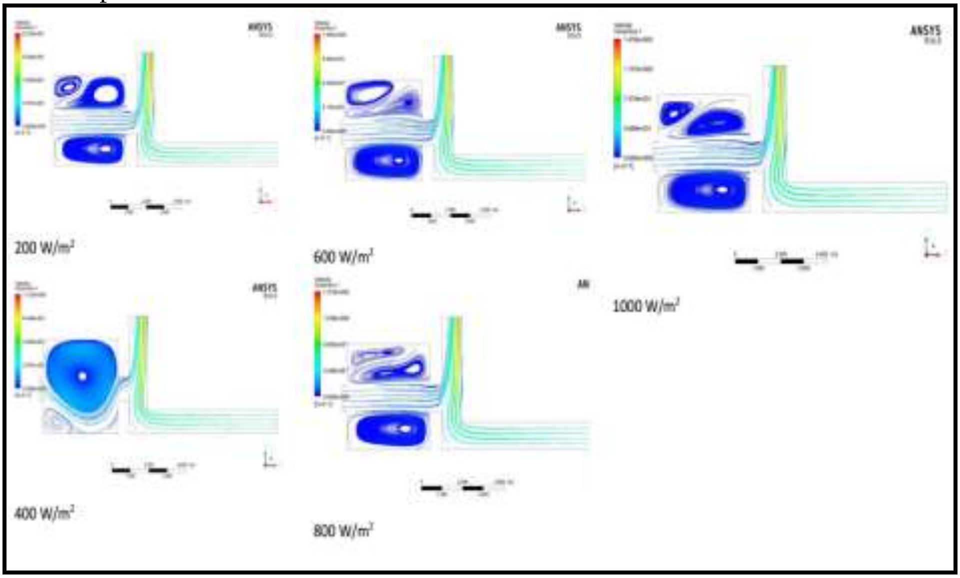

Figure 21: The flow pattern of the SC system at heat flux of 200 – 1,000 W/m^2

IV. Conclusion

In conclusion, the Solar Chimney was analysed for potentials for providing being used as a means of ventilation and electric power generation in buildings in Nigeria. The study aimed at the development of a solar chimney model for the dual purpose of passive ventilation and renewable power generation in buildings. In this study analysis were carried out using basic equations of thermos-fluids to carry out sensitivity analysis of the model. The mass flow rate increased as chimney height increases. It was also observed that the mass flow is a direct function of the solar radiation input. The power output of the system was found to increase with both increase in solar radiation and chimney height. It is therefore concluded from the performance analysis that the combined solar chimney is a feasible a means of improving energy efficiency of buildings. Furthermore, it is noted that combined solar chimney had better results at locations with higher solar radiation and wind conditions for both ventilation and power.

Reference

[1] Alex Morales (February 7, 2012). "Wind Power Market Rose to 41 Gigawatts in 2011, Led by China" (http://www.businessweek.com/news/2012-02-07/wind-powermarket-rose-to-41-gigawatts-in-2011-led-by-china.html). Bloomberg.

[2] ANSYS FLUENT Theory Guide (2011) ANSYS, Inc., Southpointe, 275 Technology Drive, Canonsburg, PA 15317, ansysinfo@ansys.com, http://www.ansys.com, Release 14.0 November 2011.

[3] Arce, J., Jimenez, M. J., Guzman, J. D., Heras, M. R., Alvarez, G., Xaman, J. (2009). Experimental study for natural ventilation on a solar chimney. *Renewable Energy*, 34: 2928-2934.

[4] Bar-Cohen, A. & Krauss, A.D. (1988). Advances in Thermal Modeling of Electronic Components and Systems. Hemisphere Publishing Corporation, New York.

[5] Ben Sills (Aug 29, 2011). "Solar May Produce Most of World's Power by 2060, IEA Says". *Bloomber http://www.bloomberg.com/news/2011-08-29/solar-may-produce-most-of-world-s-power-by-2060-iea-says.html* (viewed 1st Nov. 2012)

[6] Bilgen, E. & Michel, J., (1979). Integration of solar systems in architectural and urban design. In: Sayigh, A.A.M. (Ed.), *Solar Energy Appl Build*. Academic Press, New York.

[7] Burek, S.A.M., Habeb, A. (2007). Air flow and thermal efficiency characteristics in solar chimneys and Trombe Walls. *Elsevier, Energy and Buildings* 39: 128–135.

[8] Chen, Z.D., Bandopadhayay, P., Halldorsson, J., Byrjalsen, C., Heiselberg, P., Li, Y. (2003). An experimental investigation of a solar chimney model with uniform wall heat flux. *Building and Environment*, 38: 893-906.

[9] Ekechukwa, O.V. & Norton, B. (1999). Review of solar energy drying system II. An overview of solar drying technology. *Energy Conserv. Manage*. 40: 615–655.

[10] DeBlois J., Bilec M., Schaefer L. (2013). Simulating home cooling load reductions for a novel opaque roof solar chimney configuration. *Applied Energy,* 112: 142–151.

[11] Fluri T. P., von Backstrom T. W. (2008a). Comparison of modelling approaches and layouts for solar chimney turbines. *Solar Energy,* 82: 239–246.

[12] Fluri T. P., Von Backstrom T. W. (2008b). Performance analysis of the power conversion unit of a solar chimney power plant. *Solar Energy,* 82: 999–1008.

[13] Gontikaki, M., Trcka, M., Hensen, J.L.M. & Hoes, P. (2010). Optimization of a Solar Chimney Design to Enhance Natural Ventilation in a Multi-Storey Office Building. Proceedings of 10th International Conference for Enhanced Building Operations, Kuwait: ICEBO.

[14] Hirunlabh J, Kongduang W, Namprakai P, Khedari J. (1999). Study of natural ventilation of houses by a metallic solar wall under tropical climate. *Renewable Energy,* Volume 18:109–19.

[15] Koronaki I. P. (2013). The impact of configuration and orientation of solar thermosyphonic systems on night ventilation and fan energy savings. *Energy and Buildings,* 57: 119–131.

[16] Liu W., Ming T. and Yang K. (2005). Simulation of Characteristics of Heat Transfer and Flow for MW Grade Solar Chimney Power Plant. Proceedings of ISEC 2005, 2005 International Solar Energy Conference, August 6-12, 2005, Orlando, Florida. ISEC2005-76221.

[17] Maerefat M., Haghighi A. P. (2010a). Natural cooling of stand-alone houses using solar chimney and evaporative cooling cavity. *Renewable Energy,* 35: 2040–2052.

[18] Maerefat M., Haghighi A. P. (2010b).Passive cooling of buildings by using integrated earth to air heat exchanger and solar chimney. *Renewable Energy,* 35: 2316–2324.

[19] Mathur, J., Bansal, N. K., Mathur, N. K., Jain, M., Anupma. (2006). Experimental investigations on solar chimney for room ventilation. *Solar Energy,* 80: 927-935.

[20] Nouanégué, H.F. & Bilgen, E. (2009). Heat transfer by convection, conduction and radiation in solar chimney systems for ventilation of dwellings, *Elsevier, International Journal of Heat and Fluid Flow*, 30: 150–157.

[21] Ortega E. P. (2011). Analyzes of Solar Chimney Design. Master's Thesis submitted to

the Norwegian University of Science and Technology, Department of Energy and Process Engineering July 2011. 82 Pages.

[22] Petela R. (2009). Thermodynamic study of a simplified model of the solar chimney power plant. *Solar Energy*, 83: 94–107.

[23] Pretorius, J. P. & Kröger, D. G. (2006). Critical evaluation of solar chimney power plant performance. *Elsevier, Solar Energy*, 80: 535–544.

[24] Pretorius, J. P. & Kröger, D. G. (2009). The Influence of Environment on Solar Chimney Power Plant Performance. *R & D Journal, of the South African Institution of Mechanical Engineering*, *25*. http://www.saimeche.org.za (open access)

[25] Renewables 2011 Global Status Report (2011). http://www.ren21.net/Portals/97/documents/GSR/GSR2011_Master18.pdf (viewed 1st Nov. 2012).

[26] Odia, O. O., Ososomi, S. A., & Okokpujie, P. I. (2016). Practical Analysis of A Small Wind Turbine for Domestic Use on Latitude 7.0670 N, Longitude 6.2670 E. *Journal of Research in Mechanical Engineering*, *2*(11), 8-10.

[27] Schlaich J. (1995). The solar chimney: electricity from the sun. In: Maurer C, editor. Germany: Geislingen

[28] Schlaich, J., Wolfgang S. (2000). Solar Chimneys, Encyclopedia of Physical Science and Technology, Third Edition.

[29] Sudaporn C. and Bundit L. (2006). A Numerical Study of Natural Ventilation in Buildings - Utilized Solar Chimney and Cool Ceiling. The 2nd Joint International Conference on "Sustainable Energy and Environment (SEE 2006)" November 2006, Bangkok, Thailand B-043 (P) 21-23.

[30] United Nations Environment Programme: *Global Trends in Sustainable Energy Investment 2007: Analysis of Trends and Issues in the Financing of Renewable Energy and Energy Efficiency in OECD and Developing Countries*, sefi.unep.org/fileadmin/media/sefi/docs/publications/SEFI_Investment_Report_2007.pdf (viewed 1st Nov. 2012)

[31] Zhou X. P., Yang J. K. and Xiao B. (2007a). Improving natural ventilation in combined solar house with solar chimney and solar water collector. *Journal of the Energy Institute*, Volume 80(1): 55-59.

[32] Zhou, X. P., Yang, J. K., Xiao, B. & Hou, G. (2007b). Simulation of a pilot solar chimney thermal power generating equipment. *Elsevier Renewable Energy*, 32: 1637–1644.

[33] Zhou, X. P., Yang, J. K., Xiao, B., Hou, G. & Xing, F. (2009). Analysis of chimney

height for solar chimney power plant. *Elsevier Applied Thermal Engineering*, 29: 178-185.

[34] Zhou, X. P., Wanga, F., Fan J. and Ochieng, R. M. (2010). Performance of solar chimney power plant in Qinghai-Tibet Plateau. *Elsevier Renewable and Sustainable Energy Reviews*, 14: 2249–2255.

[35] Osueke, C. O., Uzendu, P., Ogbonna, I. D. (2013), Study and Evaluation of Solar Energy Variation in Nigeria. International Journal of Emerging Technology and Advanced Engineering, 3(6): 501 – 505.