DEVELOPMENT AND PERFORMANCE INVESTIGATION OF A NOVEL SOLAR CHIMNEY POWER GENERATION SYSTEM

By

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Submitted in partial fulfilment of the requirements for the degree

DOCTOR TECHNOLOGIAE

in the

Department of Mechanical Engineering, Mechatronics and Industrial Design

FACULTY OF ENGINEERING AND THE BUILT ENVIRONMENT

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March 2015
DECLARATION

I hereby declare that the dissertation entitled DEVELOPMENT AND PERFORMANCE INVESTIGATION OF A NOVEL SOLAR CHIMNEY POWER GENERATION SYSTEM has been submitted in accordance with the requirements for the degree of Doctor Technologiae in Engineering and the Built Environment at the Department of Mechanical Engineering, Mechatronics and Industrial Design at the Tshwane University of Technology. I further declare that the dissertation is my own work and that all references used and quoted have been acknowledged.

________________________________________
L.W. Beneke
2015

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ACKNOWLEDGEMENT

The experience of completing this research report was challenging, extremely rewarding and a valuable learning experience. I would not have been able to undertake this work alone and would like to express my gratitude to the following individuals:

• Dr. C.J.S. Fourie, my supervisor, for his professional guidance, academic rigor, encouragement and patience during the completion of this study.
• Prof Z Huan, my co-supervisor, for his enthusiastic support, valuable input and attention to technical detail.
• Rita, Rynhardt and Bianca for encouragement, support and understanding.
• Wenzel and Bertie (running partners) for encouragement and support.
• The Beneke, Stapelberg and Vorster families for their support.

I would like to express my gratitude and appreciation to the Department of Mechanical Engineering, Mechatronics and Industrial Design, Faculty of Engineering and the Built Environment for their support and understanding. I would like to express my gratitude and appreciation to the students in the workshop of the Department of Mechanical Engineering, Mechatronics and Industrial Design, Faculty of Engineering and the Built Environment for their support and manufacturing of the prototype.
ABSTRACT

South Africa has limited reserve electricity resources and many parts of the country have limited access to electricity. Electricity production capacity is at maximum and almost each Giga watt is accounted for. Predictions suggest South Africa would have a serious electricity allocation problem in the very near future and current rolling blackout in many of our cities can attest to the looming problem. The energy crisis in South Africa has highlighted the need to increase electricity generation capacity and to search for alternative energy sources.

Solar chimney plants could form part of the solution in the near future in South Africa to create additional power. Solar radiation energy is abundant in South Africa, while wind sources are limited to some coastal regions. Presently, wind turbine technology is more effective than solar voltaic cells. This study aimed to develop a wind generation system in areas where wind is absent. A solar chimney power plant is expected to provide remote areas in South Africa with electric power, or to complement the current electricity grid. Solar energy and the psychometric state of the air are important to encourage the full development of a solar chimney power plant for the thermal and electrical production of energy for various uses. A solar chimney power plant consists of a collector and the chimney is located at the centre of the collector which is usually made of a glass plate that traps the solar energy and increases the total air enthalpy. The chimney is used to direct and vent the low density air through the wind turbine which in turn converts the air enthalpy into mechanical energy. The main advantage of a solar chimney system lies in its low maintenance cost, simplicity of operation and the durability of the system.

Research within the South African context and particularly on increasing the effectiveness of the solar chimney power plant technology is lacking; as such this study proposes the development of a solar chimney plant and associated technology to ensure the effectiveness of this plant.

The project had the following steps:
(a) Preliminary numerical comparison between the conventional design and the proposed design,
(b) Numerical modelling to evaluate thermodynamic properties of the system,
(c) The development of a laboratory set-up for testing the efficiency of a solar power plant,
(d) Evaluation of the effectiveness and energy-optimal application of the solar power plant and
(e) Evaluation of the potential viability for a pilot solar power plant system.

This performance of the solar power plant, which was the focus of this research project, was evaluated by generating three different sets of data. These were:

- Theoretical and numerical simulation performance results using the ANSYS software. During the numerical simulations of the pilot plant without mirrors, two different situations were evaluated. These were for a winter’s day and a summer’s day. The average power output for a typical winter’s day in Pretoria was 15.562 mW and 23.452 mW for a typical summer’s day respectively.

- The long term measurement of the performance of the constructed pilot plant with a data logger (voltage and power). The physical dimensions of the pilot plant were exactly the same as with the numerical simulations to allow a direct comparison between the two data sets. The measured power output for a typical winter’s day was 15.181 mW and 25.724 mW for a typical summer’s day respectively.

- Lastly, measurements (voltage and power) of the constructed pilot plant with mirrors were also performed, although it was not simulated in ANSYS. This was done because it was a relatively easy task to construct the mirrors, and the data measuring system was in place. The measured power output for a typical winter’s day with mirrors was 4.344 mW and 65.279 mW for a typical summer’s day respectively.

The results showed that the power output is larger in summer than in winter, and showed that simulated and measured pilot plant without mirrors are in agreement. The results of the pilot plant with mirrors are much larger due to the increased radiation.
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<tbody>
<tr>
<td>A</td>
<td>Area, m²</td>
</tr>
<tr>
<td>A_{flow}</td>
<td>Flow area, m²</td>
</tr>
<tr>
<td>b</td>
<td>Breadth, m</td>
</tr>
<tr>
<td>C</td>
<td>Circle diameter, m</td>
</tr>
<tr>
<td>C_{air}</td>
<td>Heat Capacity of air = 0.0342, J/kg K</td>
</tr>
<tr>
<td>C_D</td>
<td>Discharge coefficient (usually taken to be from 0.65 to 0.70)</td>
</tr>
<tr>
<td>C_v</td>
<td>Heat Capacity of air at a constant volume, J/kg K</td>
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<td>d_c</td>
<td>Top outlet diameter of the chimney, m</td>
</tr>
<tr>
<td>D</td>
<td>Diameter for straight chimney, m</td>
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<tr>
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<tr>
<td>D_p</td>
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</tr>
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<tr>
<td>E_k</td>
<td>Kinetic Energy, J</td>
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<td>FG</td>
<td>Indicator for occurrence of: Fog</td>
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<tr>
<td>g</td>
<td>Gravity acceleration = 9.81, m/s²</td>
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<td>Height, m</td>
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<td>Inlet aperture, m</td>
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<tr>
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<td>Mass, kg</td>
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<td>Mass flow rate, kg/s</td>
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<td>Flow rate, m³/s</td>
</tr>
<tr>
<td>r</td>
<td>Radius, m</td>
</tr>
<tr>
<td>RA</td>
<td>Indicator for occurrence of: Rain or Drizzle</td>
</tr>
<tr>
<td>R_{air}</td>
<td>Air constant = 287.058, J/Kg K</td>
</tr>
<tr>
<td>s</td>
<td>Square diameter, m</td>
</tr>
<tr>
<td>SLP</td>
<td>Mean sea level air pressure, hPa</td>
</tr>
<tr>
<td>SN</td>
<td>Indicator for occurrence of: Snow or Ice Pellets</td>
</tr>
<tr>
<td>------</td>
<td>-----------------------------------------------</td>
</tr>
<tr>
<td>T</td>
<td>Temperature, K</td>
</tr>
<tr>
<td>$T_i$</td>
<td>Absolute inside temperature, K</td>
</tr>
<tr>
<td>TM</td>
<td>Maximum temperature, °C</td>
</tr>
<tr>
<td>Tm</td>
<td>Minimum temperature, °C</td>
</tr>
<tr>
<td>$T_o$</td>
<td>Absolute outside temperature, K</td>
</tr>
<tr>
<td>TS</td>
<td>Indicator for occurrence of: Thunder</td>
</tr>
<tr>
<td>VE</td>
<td>Mean wind speed, Km/h</td>
</tr>
<tr>
<td>V</td>
<td>Velocity, m/s</td>
</tr>
<tr>
<td>VG</td>
<td>Maximum wind gust, Km/h</td>
</tr>
<tr>
<td>VM</td>
<td>Maximum sustained wind speed, Km/h</td>
</tr>
<tr>
<td>VV</td>
<td>Mean visibility, Km</td>
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<tr>
<td>$W_{turbine}$</td>
<td>Power of turbine, W</td>
</tr>
<tr>
<td>$\Delta P$</td>
<td>Available pressure difference, Pa</td>
</tr>
<tr>
<td>$\Delta T$</td>
<td>Available temperature difference, K</td>
</tr>
</tbody>
</table>

**Greek symbols**

$\rho$  Density, kg/m$^3$

$\eta$  Efficiency, %

$\gamma$  Specific heat ratio

**Subscripts**

1  Inlet of the solar collector
2  Inlet of the wind turbine/outer of the solar collector
3  Inlet of solar chimney/outlet of the wind turbine
4  Outlet of solar chimney
CHAPTER 1

1 INTRODUCTION

1.1 Background

South Africa generates 77% of its electricity in coal-fired power stations, with the remaining 23% from the smaller hydropower and Koeberg nuclear stations (Eskom 2010). The state-controlled Eskom company is the main customer of the coal mined in the country, being supplied with about 111 million metric tonnes (Mt) in 2007 (Ikaneng, 2008). Secure electricity supply continues to be a significant factor in the economic growth of South Africa. Although the planned power outages that were enforced in late 2008 until January 2009 were repeated in late 2014, Eskom is under pressure to ensure that it fulfils its mandate to supply South Africa with adequate electricity. However, this situation is worsened due to the fact that South Africa is not completely supplied with electricity (Figure 1). In an effort to increase its electricity output, Eskom has built the Medupi coal-fired power station alongside its sister unit Matimba, in the Limpopo Province. Both will source their coal from the nearby Grootegeluk Mine.

Figure 1: Energy source for heating in South Africa (SOER, 2011)
Although the movement away from coal fired power stations will be slow due to political aspects, there will be significant future challenges to overcome (Jeffrey, 2005b). These include the scarcity of water resources for power generation and coal processing, the relatively under-developed infrastructure and the need for new mining methods to fully exploit the coal seams.

Increasing energy demand and the large quantities of fossil fuels being used in South Africa has generated extensive environmental concerns and has driven the development of alternative energy sources. Solar energy is abundant in South Africa (Figure 2). The solar radiation energy varies from 6000 MJ/m$^2$ to 9500 MJ/m$^2$, per year, (CSIR, 2009), which makes solar energy applications very attractive.

![Figure 2: Annual direct and diffuse solar radiation (DME, Eskom, CSIR, 2001)](image)

Increasing energy demand and the major exploitation of fossil fuels has generated extensive environmental concerns. A solar chimney power plant offers interesting opportunities to use pollution-free resources of renewable energy. A solar chimney is a natural power generator that uses solar radiation to increase the internal energy of flowing air. The mechanical energy generated by moving air can be transformed into electric power through a suitable wind turbine. The solar chimney power plant concept and a description were presented by Isidoro Cabanes (1903), a colonel in the Spanish army (Larbi et al., 2010).
The concept of the first solar chimney power technology was based on the principle that in the collector, solar radiation is used to heat an absorber (ordinarily soil or water bags) on the ground. This absorber heats a large body of air which rises up through the chimney due to the density difference of the air between the chimney base and chimney top. This creates a draft or “artificially created wind” through the chimney which, in turn, drives turbines that generate electricity. This plant was observed to produce an upwind velocity of 15 m/s under no load conditions. The highest power output reached was 50 kW from July to September in 1982 (Zhou et al, 2007).

A schematic diagram (Hamdan, 2010) of the solar chimney power plant is presented in Figure 3. A simplified model is used to describe the power plant including the three major components, which are the solar collector, the chimney and wind turbine. The physical dimensions in the model focus on the chimney height and diameter and the collector diameter.

Figure 3: Schematic diagram showing the basic elements of a solar chimney power plant (Hamdan, 2010).
1.2 Problem Statement
The use of wind power for generating electricity has been constantly and rapidly increasing over the last few decades. According to all predictions and goals set by international authorities, this trend is likely to continue. However, further increases of wind power exploitation require the production of larger wind turbines with higher unit power output (Jelavic et Al., 2008; Tadzhiev et Al., 2009).

This project is an alternative design focusing on very low wind potential areas where an effective cone solar frustum power plant is able to generate sufficient wind flow to turn a turbine and produce electricity. The project will focus on four aspects:

- Tower, tower base and mirrors, which will include the structure and physical configurations of chimney tower.
- Heat transfer areas.
- Wind turbine blade configurations, and
- Efficiency of the turbine.

The creation of optimum air flow through the tower will depend on the design of the tower configuration, the base of the tower which acts as a heat capacitor and the mirrors to reflect additional radiant energy onto the tower. These will also act as the heat transfer areas to instigate the air flow that will turn the turbine.

The turbine blade configurations will determine the size of the plant. Different options will be investigated to optimize the size to power output ratio. This will then be coupled directly towards the efficiency of the system.

1.3 Sub-Problems
The sub problems listed below will be handled in a chronological order and successive steps will only be conducted upon successful completion of preceding steps. The first step will be the use of a mathematical model (Computational Fluid Dynamics Software) to simulate the system and it will focus on the following issues (Kreith et al., 2007; Incropera et al., 2007 and Zhou et al., 2010):

- Heat transfer in the cone frustum
- Energy balance in the cone frustum
• Momentum balance in the cone frustum
• The air flow in the cone frustum
• The effect of the bottom and top diameter of the cone frustum to obtain the optimum air flow.
• The effective height of the frustum of cone according to air flow.

The second step will involve the construction of a scale or “bench” model of the solar cone frustum. During this phase, heat will be supplied to simulate the air flows and to investigate empirically the optimum parameters through experimental observations and to evaluate the numerically modelled results. The power output will also be measured and correlated with the modelled results.

The third step will be the construction of a pilot solar cone frustum power plant to generate electricity if the preceding steps above prove successful. The fourth and final step will be the thorough testing of solar cone frustum power plant, as follows:

• Effective and sufficient air flow
• Influence of cone frustum height to bottom and top diameters
• Influence of ambient temperature and solar irradiance on the generation of electricity
• Influence of ambient temperature and solar irradiance on the ground temperature
• Influence of ambient temperature and solar irradiance on the exit air temperature
• Air temperature distributions through the cone frustum
• Average electricity produced

1.4 Hypothesis
It is envisaged that the proposed solar cone frustum power plant can generate power which will compare favourably with existing chimney power plant systems, with a more favourable cost analysis.
1.5 Research aims
The overarching aim of the proposed study is to design and evaluate the use of an alternative solar chimney power plant for the creation of electricity. More specific aims include:

- Comparison of the traditional cylindrical shape chimney with an octagon shaped chimney
- Chimney profile effectiveness
- The study on the efficiency of heat transfer through the chimney
- The study on the height of the chimney according to the efficiency of the air flow and temperature
- Design of a modular solar cone frustum power plant for simple construction
- Comparison of numerical simulations to pilot plant performance without and with mirrors.

Air flow and temperature will be the basis of comparison of the proposed system to others currently in use.

1.6 Research Methodology
The research procedure will be undertaken as follows:

- A comprehensive literature study will be conducted to determine if any additional attempts have been made to develop and utilise a solar cone frustum power plant to generate electricity
- Following the literature study, the design of the system will be numerically modelled to determine the optimum parameters for the construction of the “bench model”.

In order to simplify this technology, some assumptions are adopted as follows:

- The height of the collector from the ground was considered small enough to disregard the pressure drop in the collector section. This assumption is applicable since the cross-sectional flow area in the collector is much larger than the chimney cross-sectional area (Hamdan, 2010).
- The heat radiated to the chimney from the collector is ignored since the surface area of the collector is much larger than the surface area of the
chimney. Therefore, the heat transfer equation is considered for the collector and cone frustum (Hamdan, 2010).

- The turbine efficiency is not considered in the calculations (Hamdan, 2010).
- Heat transfer from the system to the surrounding air was ignored and only heat transferred from surrounding air to the collector and cone frustum are considered (Hamdan, 2010).
- The analysis is based on transient thermal-fluid assumptions which are an approximation because solar radiation is transient in nature (Hamdan, 2010).
- The flow is incompressible across the chimney, since the Mach number is below 0.3 (Hamdan, 2010).
- Average uniform solar heat flux over the period of 24 hours (one day) is used in the calculation (Hamdan, 2010).

The actual physical experimental construction will only take place following the modelling investigation. The preliminary testing phase will commence once the experimental set-up is completed. The research will then focus on various experimental designs to determine optimum energy generation. If successful, it is envisaged that a full working pilot plant be constructed for final testing.
CHAPTER 2

2. LITERATURE SURVEY

2.1 History
In the early twentieth century, Isidoro Cabanyes (1903), a colonel in the Spanish army, proposed a solar chimney power plant in the magazine La energia electrica (Figure 4).

Figure 4: Picture of the solar frustum constructed by Isidoro Cabanyes in 1903 (after Cabanyes, 1903)
The article included the construction details of the proposed solar frustum. It used a surface suitable for heating and consisted of a compact lattice of iron wire 1½ to 2 mm in diameter, and formed square meshes of 1½ or 2 mm. The straight side of the chimney section must have the heating surface ratios of 1/12, 1/15 and 1/18, depending on the height of the chimney, which could then be 20, 25 or 30 meters.

The project was extraordinary at the time but was not difficult to construct and it used a square base of 12 m by 12 m or 144 m². Calculations at the time suggested that the height of the chimney needed to be 63.87 m if a power output of 65 horsepower was needed.

Cabanyes suggested that combined sun and wind action will enable the solar power plant to work at least eight hours daily throughout the whole year. However, Isidoro Cabanyes never constructed his proposed solar power plant.

In 1926, Bernard Dubos, a professional engineer (Hamilton, 2011) proposed to the French Academy of Sciences the construction of a Solar Aero-Electric Power Plant in North Africa with its solar chimney on the slope of a large mountain (Figure 5).

![Solar power plant design of Dubos (1926) against a mountain in Algeria.](image)
As a matter of fact, Dubos had the North African Atlas Mountains in mind when he developed his design. The mountain could be a large heat source and is about 5000 ft high. He claimed that an ascending air speed of 50 m/s can be reached in the chimney, due to the large temperature and pressure differences between the surface and the top of the mountain. This enormous amount of energy can be extracted by wind turbines. In 1956 he filed his first patent in Algeria. The design artificially generated an atmospheric vortex in a sort of a round-shaped Laval nozzle which recovers some energy through turbines. He received a French patent for his invention in 1964.

Another early description was published in 1931 by German author Hanns Günther (Figure 5). This was his pseudonym (Hilz et.al., 1962) and his real name was Walter de Haas (1886-1969).

The proposal of Günther suggested that the ground underneath the solar collector is heated sufficiently for the generation of electricity for a full 24 hours per day. He also suggested that other energy storage mediums such as water and oil can be used to ensure longer operation after nightfall. Locating a tower at high mountain ranges
could produce up to 85 per cent of the output of a similar plant located closer to the equator, if the collection area is sloped correctly. The slope collector field is built on suitable mountainsides, which also functions as a chimney. A short vertical chimney on the mountaintop will accommodate the vertical axis air turbine. Results showed that solar chimney power plants at high ranges may have satisfactory thermal performance (http://en.wikipedia.org/wiki/Solar_updraft_tower).

In the beginning of 1975, Robert E. Lucier filed more complex patents for a solar chimney electric power generator. Between 1978 and 1981 patents were granted in Australia, Canada, Israel and USA (http://en.wikipedia.org/wiki/Solar_updraft_tower).

Starting in 1982, a team led by the German civil engineer Jörg Schlaich took the initiative and constructed a prototype in Ciudad Real Manzanares, 150 km south of Madrid in Spain (Figure 7). The solar tower was built of iron plating only 1.25 millimetres thick. The plant had a 200 m high chimney and a maximum power output of 50 kW (Von Backström et al., 2008). The plant operated for eight (8) years. During the operation, 180 sensors measured inside and outside temperature. Humidity and wind speed data was collected on a second by second base.

![Figure 7: Solar power plant at Manzanares, Spain.](image)
The tower guy-wires were not protected against corrosion and failed due to rust and strong storm winds. The tower blew over and was decommissioned in 1989. In 2002, Time Magazine identified this project as one of the best inventions of the year. The operating principle is considered revolutionary but is based on a very common phenomenon: warm air rises. Importantly, this experiment did not sell energy.

2.2 The Solar Collector

Significant research has been put into the construction, simulation and operation of solar chimney collectors. Two types were tested by Pasumarthi and Sherif (1997). The first type extends the collector base and the second introduces an intermediate absorber. The experimental temperatures reported are higher than the theoretical temperatures. The explanation offered by the authors was that the experimental temperatures reported are the maximum temperatures attained inside the chimney, whereas the theoretical model predicts the bulk air temperatures.

Lombaard et al., 2002 investigated the temperatures of the insulated collector plate and glass cover of a horizontal solar collector. It was compared to theoretically predicted values for different ambient conditions (Figure 8). By employing an appropriate equation for the prediction of the heat transfer between the cover and the natural environment, good agreement was obtained between the theoretically predicted and experimentally measured values.

Figure 8: Temperature and thermal interactions of the insulated collector plate (Lombaard et al., 2002)
Hamdan (2004) presented an analytical model to predict the performance of a solar chimney power plant. Hamdan found that the design of the turbine head have a very strong effect on the second-law efficiency and total harvested power. In 2005, E. Bilgen and J. Rheault (Figure 9) proposed the construction of the solar collector in a sloped and tapered (with high altitude) section. This is a new idea because the angle of inclination would aid in providing a sufficient and effective area of the collector to receive solar radiation, thereby improving the solar collector efficiency to increase the amount of useful heat needed to warm up the cold air.

Figure 9: Tapered collector for a solar chimney (Bilgen and Rheault, 2005).

Pretorius and Kroger (2006) evaluated the influence of a developed 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.

Bernardes et al. (2003) developed a comprehensive mathematical model to analyze a large scale solar chimney power plant system utilizing a single and a double collector canopy (effectively an energy storage layer). The turbine performance was evaluated by comparing simulation predictions to experimental results from the prototype plant at Manzanares, and evaluated the operational control strategies applicable to the plant.
Amel et al. (2013) suggests using a collector with a nerve like structure (Figure 10), which is a partial deviation of the main functions of the collector, which are: (1) collecting heat and (2) transporting hot air to the tower. However, this is a theoretical concept and improved collector performance is yet to be proven.

Figure 10: Amel et al. solar collector configuration (2013).

2.3 The Chimney

The chimney or tower tube is the main characteristic of a solar chimney power plant. The tower or chimney is located at the centre of the collector or greenhouse canopy and is the thermal engine for the plant. The tower creates a temperature differential between the cool air at the top and the heated air in the collector at the bottom. This creates the chimney effect, which sucks air from the bottom of the tower out at the top.

The chimney of the plant is extremely high and needs a stable base while allowing free flow of air through the turbine. It is also advantageous to have the turbine as low as possible in the chimney to make its construction simpler. There are various different methods for constructing such a tower. It includes free-standing reinforced concrete tubes, steel sheet tubes supported by guy wires, or a cable-net construction with a cladding of sheet metal or membranes (Figure 11).
The design procedures for such structures are all well established and have already been utilized for power station cooling towers. Detailed static and structural-mechanical investigations have shown that it is expedient to stiffen the tower in several stages, so that a relatively thin wall material will suffice. A solution is to use bundles of strands in the form of flat-spoked wheels which span the cross-sectional area of the tower. This is perhaps the only real structural novelty in these towers as compared to existing structures.

Schlaich (1994) suggested that reinforced concrete is the best building material for high towers. Studies have shown that this method of construction is the most sustainable and cost-effective. Such towers can also be constructed using other technologies including guyed steel towers, in which the frame is covered with nets of steel cables, membranes or trapezoidal metal films. The maximum height for this type of solar chimney is 1000 m.
2.4 The Turbines

The turbine of the solar chimney is a very important component of the solar plant as it converts the energy from the kinetic energy of air into electricity. Air and mass flow rate have a significant influence on the electricity production and is negatively influenced as the pressure drop over the turbine.

The specifications for solar chimney turbines are in many aspects similar to those for large wind turbines. Both convert large amounts of energy in the air flow into electrical energy. However, there are also various important differences. The following characteristics are typical for solar chimney turbines in contrast to normal wind turbines (Von Backström et al., 2008).

In solar chimney power plants the turbines are ducted, and their maximum theoretical efficiency is therefore 100% (the Betz-limit). This is because the direction of the incoming air flow is known and theoretically remains constant. The turbines are protected from harsh weather conditions but have to cope with higher temperatures.

The large volume of the collector and the chimney acts as a buffer and prevents large fluctuations in air flow speed, resulting in comparatively low dynamic loads on the turbine blades and all other rotating components. Furthermore, the turbine pressure drop in solar power plants is about 10 times larger than in open wind turbines (Von Backström et al., 2008).

Various turbine layouts and configurations have been proposed for solar chimneys (Figure 12). A single vertical axis turbine without inlet guide vanes was used in the pilot plant in Manzanares (Schwarz and Knauss, 1981). Configurations with multiple vertical axis turbines have been proposed as well (Schlaich, et al., 1995), and turbine layouts consisting of one pair of counter-rotating rotors, either with or without inlet guide vanes (Denantes and Bilgen, 2006).
The air circulation inside the plant, the pressure drop and the flow rate can be adjusted by varying the pitch angle of the blades of the turbine (Schwarz and Knauss, 1981).

Figure 12: Various turbine layouts and configurations proposed for solar chimneys (Schwarz and Knauss, 1981).

Many studies were conducted to evaluate the pressure drop across the turbine as a part of the total available pressure difference in the system. Gannon & Von Backström (2003) investigated the performance of solar power plant turbines and developed analytical equations to describe turbine flow. These authors also
developed the load coefficient to express the influence of each coefficient on turbine efficiency.

The objective of this work was to predict solar chimney turbine efficiency and operating characteristics to assist in solar chimney power plant design. Ming et al., (2008) performed numerical simulations for the MW-graded solar chimney power plant, investigating the effect of pressure drop across the turbine on the draft in the chimney and the power output of the system. The turbine considered in this study is of the axial type, with radial inflow inlet guide vanes (stator blades) (Figure 13).

Figure 13: Solar chimney turbine layout (Ming et al., 2008).

Von Backström and Fluri (2006) developed two different analyses to maximize fluid power by finding the optimal ratio of turbine pressure drop to the available pressure drop in a solar chimney. Their study was an analytical investigation of the validity and applicability of the assumption that, for maximum fluid power, the optimum ratio of turbine pressure drop to available pressure (the available system pressure difference) should be 67%.

Two preliminary design parameters were also considered for the operating conditions of solar chimney turbines. The assumption was that two counter-rotating turbines will be used; one with inlet guide vanes and the other without. It was compared to a single-runner system. The design and off-design performances were weighed against three different solar chimney plant sizes. In this study Denantes and Bilgen (2006) have concluded that the counter-rotating turbines without guide
vanes have lower design efficiency and a higher off-design performance than a single-runner turbine.

Nizetic et al. (2010) developed a contradictory simplified analytical approach to that of Von Backström and Fluri (2006) for evaluating the factor of turbine pressure drop in solar chimney power plants; except that this was for a single turbine only. This factor (or pressure drop ratio in turbines, according to the total pressure drop in the chimney) is important because it is related to the output power. It was concluded that for solar chimney power plants, turbine pressure drop factors are in the range of 0.8 to 0.9. This simplified analytical approach is useful for the preliminary analysis and fast evaluation of the potential of solar chimney power plants.

2.5 Turbine Coupling

Using the Spanish prototype as a practical example, Tingzhen et al. (2008) performed a numerical simulation of a solar chimney power plant system coupled with a 3 blade turbine. This study showed that the average velocity of the chimney outlet and the mass flow rate decrease with the increase of turbine rotational speed. The authors concluded that the average temperature of the chimney outlet and the turbine pressure are inversely related. The design has to seek the peak maximum available energy, power output and efficiency of the turbine.

Koonsrisuk et al. (2010) conducted a study in which the collector, chimney and turbine are modelled together. The purpose was to estimate the power output of solar chimneys as well as to examine the effect of solar heat flux and structural dimensions on the power output. Results from the mathematical model were validated by measurements from the physical plant actually built. The results show that the plant size, the factor of pressure drop at the turbine and the solar heat flux are the important parameters affecting the performance.

Ming et al. (2012) conducted a study considering the turbine as a reversed fan with a fixed pressure drop across it. A group of values ranging from 0 to 200 Pa at intervals of 20 Pa were assumed. Comparison of the simulated results to the Spanish prototype with a 3-blade turbine showed that the average velocity of the chimney
outlet and the system mass flow rate decreased with the increase in turbine rotational speed. The average temperature of the chimney outlet and the turbine pressure drop are inversely related. The maximum available energy, power output, and efficiency of the turbine each have a peak value.

2.6 Energy Storage in the Collector

The ground under the collector roof behaves as a storage medium, and can even heat up the air for a significant time after sunset. The efficiency of a solar chimney power plant depends mainly on the height of the tower and the size of the collector. As a result, these power plants can only be constructed on large land that is very cheap or free. Such areas are usually situated in rural or desert regions. However, this approach is not without other uses, as the outer area under the collector roof can also be utilized as a greenhouse for agricultural purposes (Chikere et al., 2011).

An alternative approach is water filled black tubes (as an energy reservoir) that are laid down side by side on the black sheeted or sprayed soil under the glass roof collector (Figure 14). They are filled with water once and remain closed thereafter, so that no evaporation can take place. Heated water from the tubing is circulated to a heat exchanger in the chimney. The volume of water in the tubes is selected to correspond to a water layer with a depth of 5 to 20 cm depending on the desired power output (Schlaich, et al., 2005).

Figure 14: Principle of heat storage underneath the roof using water-filled black tubes (Schlaich, et al., 2005).
Since the heat transfer between black tubes and water is much larger than between the black sheet and the soil, heat transfer is greater even at a low water flow speed in the tubes. The heat capacity of water (4.2 kJ/kg) is much higher than that of soil (0.75 - 0.85 kJ/kg) and the water inside the tubes stores solar heat and releases it during the night, when the air in the collector cools down.

Bernardes (2004), also studied ground water storage systems of solar chimney plants and examined the effect on power generation over time. His calculations showed the possibility of continuous day and night operation of the solar chimney (Figure 15). The results show that, although ground is a good absorber of energy, it is a bad heat conductor. The pipes must not be buried too deep in the surface topsoil; otherwise power generation is decreased, as can be seen by comparison of the 10 cm and 20 cm depths.

Figure 15: Effect of heat storage underneath the collector roof using water-filled black tubes (Bernardes, 2004).

It is thus found that ground characteristics play an important role in energy absorption and transfer. Pretorius (2004) compared the power outputs achieved with six different ground types: sandstone, granite, limestone, sand, wet soil and water. The lowest and highest power outputs were attained with wet soil and sand, respectively. Different soil materials achieve varying power outputs during the
daytime and at night. Pretorius also concluded that increased ground absorptivity improves annual solar chimney power output.

Hammadi (2008) developed a mathematical model for the solar updraft tower with a water storage system and investigated the effect of the thermal storage system on the power production of the plant. The conclusion was that the water storage layer (depending on the thickness) shifted the peak value of the output power further away from mid-day values and smoothed the output curve towards a consistent output.

Tingzhen et al. (2009) studied the heat transfer and air flow in a solar chimney power plant system with an energy storage layer. The effect of solar radiation increasing from 200 W/m² to 800 W/m² on the heat capacity of the energy storage layer was analyzed. Simulation results showed that the increasing solar radiation was associated with a first phase of decreasing heat storage ratios of the layer, followed by increasing ratios. It was also found that the average temperature of the chimney outlet and the energy storage layer may increase significantly with the increase of the solar radiation.

An experimental study was conducted in Baghdad by Miqdam and Hussein (2011) focusing on air temperatures using different chimney basements. The objective was to examine the effect of basement types on the air temperatures in a prototype solar chimney designed and constructed for this purpose. Three basements were tested; concrete, black concrete and black pebbles. The highest temperature difference was reached with the pebble base.

2.7 Different Prototypes

2.7.1 The Manzanares Prototype

Schlaich Bergermann has designed, constructed and operated an experimental plant with a peak output of 50 kW on a site made available by the Spanish utility Union Electrica Fenosa in Manzanares (about 150 km south of Madrid) in 1981/82 (Figure 16), with funds provided by the German Ministry of Research and Technology (BMBF). The aim of this research project was to verify, through field measurements,
the real performance based on theory and calculations, and to examine the influence of individual components on the output of the plant and the efficiency under realistic engineering and meteorological conditions. Erection of the plant was completed in 1981, and after a phase of improvements, continuous operation started in 1983 and continued until 1989 (Schlaich, 1994).

![Figure 16: The construction of the solar updraft tower in Manzanares, Spain in 1982.](image)

The metal tower was nearly 200 m high, constructed of steel sheet rings, surrounded by an array of plastic sheeting 240 m across, acting as the collector. The main characteristics of the prototype are given in Table 1.

The developers claimed that the Manzanares plant achieved an electricity efficiency of 0.53%. It is believed that this could only be increased up to 1.3% in a large 100 MW unit. The efficiency of these plants increases with size. The capacity factor measured at Manzanares was 10%, but it is claimed this would rise to 29% in a 200 MW unit.
Table 1: Data and design values of the Manzanares pilot plant.

<table>
<thead>
<tr>
<th>Parameters of the Manzanares prototype</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tower height (m)</td>
</tr>
<tr>
<td>Tower radius (m)</td>
</tr>
<tr>
<td>Collector radius (m)</td>
</tr>
<tr>
<td>Chimney weight (kg)</td>
</tr>
<tr>
<td>Average height of the collector (m)</td>
</tr>
<tr>
<td>Number of turbine blades</td>
</tr>
<tr>
<td>Turbine blade profile</td>
</tr>
<tr>
<td>Radius velocity</td>
</tr>
<tr>
<td>Radius transmission</td>
</tr>
<tr>
<td>Collector temperature increase (°C)</td>
</tr>
<tr>
<td>Nominal output (kW)</td>
</tr>
<tr>
<td>Glass roof- collector area (m²)</td>
</tr>
</tbody>
</table>

The Manzanares plant was retrofitted with black plastic tubes containing water. Mining scrap can be used for this purpose. The SBP technology originally used plastic sheet glazing at Manzanares, but this encountered severe structural instability close to the tower due to induced vortices. Toughened glass is likely to be used for all future plants.

Because of the collector size, the array-cleaning cost is an important concern. However, other maintenance costs associated with this approach seem to be very low (Mills, 2004). The solar chimney pilot plant at Manzanares has demonstrated the technical feasibility of electricity generation with solar chimney power plants.

The electrical power output is a function of solar radiation, but also depends on meteorological and environmental conditions. The plant operated for about eight years until the chimney support wires rusted and the chimney was blown over in a storm. It did prove that the concept was scientifically sound. A meaningful output of power from such a system (megawatts instead of kilowatts) requires the construction of a substantially taller chimney and collector. A taller chimney will produce a stronger updraft and more power will be generated (Hamilton, 2011).
2.7.2 The Enviromission power plant

In 2001, a company called Enviromission announced that it planned to build a 200 megawatts solar chimney plant in southwest Australia that could generate 4 000 times more power than the Manzanares system. The Australian firm worked with the German consultants, Schlaich Bergmann. The solar chimney must be 130 m in diameter and 1 000 m tall (Figure 17). A plastic or glass covered solar collection area of up to 35 square kilometres is required to generate the required warm air flow through that chimney. The project is expected to cost nearly $ 1 billion (Hamilton, 2011).

Figure 17: Enviromission power plant scheme in Australia.

The 1 000 m tower will be constructed of reinforced concrete and strengthened by horizontal metal supports that can also act as platforms. The air temperature under the collector roof will be around 30°C and the wind speed will be about 32 km/h.

Energy will be extracted from this flow using 32 turbines set horizontally in the transition area (Maynard, 2000). The turbines will be purpose-built from lightweight alloy materials, with 10 blades coupled to synchronous generators. The turbines will receive air at around 60°C to 70°C.
Enviromission also has two planned projects for Arizona, and in 2011 secured $30 million in funding to cover early development costs. Solar chimneys are also under consideration in other parts of the world. Projects are on the drawing board for the European Union and Africa, including a solar chimney in Namibia that would reach 1.5 kilometres into the sky and require a solar collecting greenhouse covering 37 km². None of these commercial-scale projects have reached construction phase, and there is no certainty they will (Hamilton, 2011).

2.7.3 The Chinese Prototype
An experimental prototype solar chimney of 200 kW has been constructed in the region of Jinsha Bay Wuhai in Inner Mongolia (China). The total planned capacity is 27.5 MW, with a total of 2.78 million m² of desert occupied by greenhouses as a collector. The current total investment is 1.38 billion yuan. The construction of the Chinese prototype was performed in three phases (Maia, et al., 2009):

- The first phase of the project was completed between May 2009 and December 2010 and included a prototype demonstration solar chimney generating 200 kW. The collector occupies 40 000 m² of desert and the tower or chimney is 53 m high and 18m in diameter. The total expenditure was 1 million yuan.
- The second phase of the project started in February 2011 and lasted until December 2011, involving the completion of a power plant based on 2.2 MW solar chimney. This demonstration system will occupy 220 000 m² of desert and the planned investment was 110 million yuan.
- The third phase of the project was planned for January 2012 and December 2013, entailing the construction of a solar chimney power plant of 25.1 MW, with a greenhouse collector occupying a desert area of 2.51 million m², the planned investment was 1.26 billion yuan (1.2 billion yuan Chinese).

2.7.4 Other Solar Chimney Plants
In December 2010, a solar updraft tower in Jinshawan, Inner Mongolia in China started operation. It produces 200-kilowatts of electric power. The cost was $208
million and the project was started in May 2009. It covers 277 hectares and is producing 27.5 MW. The greenhouses will also improve the climate by covering moving sand and restraining sandstorms (http://www.solar-tower.org.uk).

There is a proposal to construct a solar updraft tower in Ciudad Real, Spain, entitled Ciudad Real Torre Solar. If built, it would be the first of its kind in the European Union and would stand 750 meters tall. It will cover an area of 350 hectares. It is expected to have an output of 40 MW of electricity (http://www.solar-tower.org.uk).

Based on the plans for long-term energy strategies, Botswana’s Ministry of Science and Technology designed and built a small-scale solar chimney system for research (The Botswana Test Facility). This experiment ran from 7 October to 22 November 2005. It had an inside diameter of 2 m and a height of 22 m and was manufactured from glass-reinforced polyester material, with a collection base area of approximately 160 m\(^2\). The roof was made of a 5 mm thick clear glass that was supported by steel (http://www.solar-tower.org.uk).

In mid 2008, the Namibian government approved a proposal for the construction of a 400 MW solar chimney called the ‘Greentower’. The tower is planned to be 1.5 km tall and 280 m in diameter, and the base will consist of a 37 km\(^2\) greenhouse in which cash crops can be grown (http://www.solar-tower.org.uk).

A Solar updraft power plant located at high latitudes such as in Canada, could produce up to 85 per cent of the output of a similar plant located closer to the equator, but only if the collection area is sloped significantly southward. The sloped collector field should be built at suitable mountain hills, which also functions as a chimney. A short vertical chimney is added to install the vertical axis air turbine. Results of preliminary evaluations showed that solar chimney power plants at high latitudes may have satisfactory thermal performances (http://www.solar-tower.org.uk).
2.7.5 Experimental Prototypes

In 1997, a system was established by Pasurmarthi, Sheriff and Florida (Figure 18-a). They presented the construction and testing of a small scale chimney. The testing focused on the heat transfer performance of the collector and improvements thereof. The area of the roof collector was 9.15 m by 7.92 m and the chimney diameter gradually decreased from 2.44 m to 0.61 m at the summit. Absorber aluminium plate was attached to the floor under the roof of the collector (Zhou et al., 2010).

A solar chimney pilot power setup composed of a 5 m radius air collector and a chimney of 8 m in height has been built in HUST, China. The size of the opening at the periphery of the collector was chosen as 0.05 m, and was constructed to be flexible. Standard PVC drain-pipes, 0.3 m in diameter, were used as a chimney. Due to construction costs, the actual slope angle of the collector was chosen at 8°, and the height from the collector outlet to the ground level was therefore 0.8 m. The pilot solar power plant was built in December 2002 to investigate the effect of temperature variances during the day (Figure 18-b) (Zhou et al., 2007). The collector roof was made of 4.8 mm thick glass and the SC of PVC (Zhou et al., 2007). A heat insulator was used to pack the steel-frame structure of the collector, to avoid heat diffusion. Water in pipes (total diameter of 6 cm) was selected as the storing body. A one centimetre thick composite layer bed with asphalt and black gravel was applied as the top layer of the basement. The layer absorbed solar energy, and heat was transferred from the top layer to water pipes. A multiple blade designed on the operating principle of a turbine blade was installed at the base of the chimney (Zhou et al., 2007).

A pilot solar chimney plant was also built on the campus of Suleyman Demirel University, in Isparta, Turkey in the Research and Application Center for Renewable Energy Resources (RACRER). The chimney was 15 m in height with a diameter of 1.2 m. The glass-covered collector was 16 m in diameter (Figure 18-c). After the experimental studies, the system was theoretically modelled. This model constituted the basis for the development of a computer program to obtain performance parameters for the system (Üçgül and Koyun, 2011). The construction dimensions of the prototype are given in Table 2.
Table 2: Characteristics of the prototype solar chimney (Üçgül and Koyun, 2011)

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Units</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chimney height</td>
<td>(m)</td>
<td>15</td>
</tr>
<tr>
<td>Collector diameter</td>
<td>(m)</td>
<td>16</td>
</tr>
<tr>
<td>Greenhouse area</td>
<td>(m²)</td>
<td>200.96</td>
</tr>
<tr>
<td>Chimney diameter</td>
<td>(m²)</td>
<td>1.19</td>
</tr>
<tr>
<td>Inlet environmental field</td>
<td>(m²)</td>
<td>31.148</td>
</tr>
</tbody>
</table>

Based on the need for long-term energy strategies, Botswana’s Ministry of Science and Technology designed and built a pilot SC power setup for research. The SC was manufactured from glass reinforced polyester material, which had an inner diameter of 2 m and a height of 22 m. The collector roof was made of 5 mm thick clear glass supported by a steel framework. The collection area is approximately 160 m². The absorber under the roof was made of two layers of compacted soil approximately 10 mm thick and a layer of crushed stones, spread on the top surface of the compacted soil layer (Ketlogetswe et al., 2008).

An international team of three architecture and five civil engineering students with their supervisors designed and built a solar chimney in one semester as part of their interdisciplinary Archineering master's degree programme. The prototype was installed at Bauhaus University in Weimar, Germany (Figure 18-d). The system is constructed of 420 m² plastic foil at its base. The warm air travels up the 12 m chimney and creates an updraft. During its phase of operation in summer 2008, the electricity was stored in batteries which powered energy-efficient LED lights for illuminating the construction at night.

In the region of Baghdad city, Iraq, a prototype of a solar chimney power plant was designed and constructed to investigate the influence of different basement materials on the chimney air temperatures. It is composed of a circular transparent roof (6 m diameter) open at the periphery (2 cm from the ground). In the middle of the roof there is a tower (4 m tall and 20 cm in diameter) with large air inlets at its base (10 cm from the ground). The study was conducted from August to November 2010 (Figure 18-e) (Sabah and Miqdam, 2011).
Another prototype was built in Belo Horizonte (Brazil) for the validation of the mathematical and numerical models. A tower of 12.3 m high was constructed with sheets of wood and covered by fibreglass. The diameter of the tower was 1.0 m. The SC was made of a plastic thermo-diffuser film, with a diameter of 25 m, only 0.5 m above the ground. The absorber surface was constructed with concrete and painted black (Figure 18-f) (Maia et al., 2009).

A solar chimney pilot plant was established at the Adiyaman University campus (Figure 18-g) in a circular hole with a special layered ground cover. The hole was 27 m in diameter and 0.5 m deep. The groundcover consisted of aluminium foil, glass wool, sand, gravel and broken glass windscreen fragments, all covered by a top layer of asphalt. The SC consisted of 4 mm thick glass panels. The chimney height was 17 m and the diameter was 0.8 m. The chimney had an air inlet collector at the periphery with an adjustable height from 5 mm to 350 mm. The effects of environmental temperature, chimney height, the collector diameter and the value of solar radiation on the performance or effectiveness of the solar chimney was investigated.

The solar chimney model prototype constructed in Al Ain, United Arab Emirates (UAE) is shown in Figure 18-h. It consists of a 10 m by 10 m collector and an 8.25 m chimney with a diameter of 24 cm. The collector was constructed using steel beams with a steel wired network to support a semi-clear plastic cover. The collector surface is designed with an inclination to allow water drainage in the event of rain and the height of the collector varies from 0.5 m near the collector edge to 0.75 m at the collector centre (Mohammad and Obada, 2012). Data was collected for three days in December 2011. The purpose of this work was the experimental evaluation of the performance of a solar chimney and comparison with the mathematical thermal model prediction. The study focussed on the internal collector dynamic temperature, the amount of solar energy trapped within the collector, and the expected air flow within the chimney.

A report was also found of a solar chimney built in Kerman, Iran (Figure 18-i). The chimney was 60 m high and 3 m in diameter with a collector of 40 m by 40 m. This effort focussed on the economic analysis of solar chimneys. Ideas were proposed to
maximize the usage of solar energy and the maximum power of the unit was calculated (Najmi, et al., 2012).

Figure 18-j shows the first pilot solar chimney plant constructed in 2009 at Mutah University in Jordan (Al-Dabbas, 2011). More detail was not available.

An experimental setup was constructed in 2010 to measure temperatures in a solar chimney pilot plant, built at the University of Zanjan, Iran (Figure 18-k). The chimney height was 12 m and the collector had a 10 m diameter. The collector slope angle was presumably designed for maximum solar radiation absorption. The collector was 1 m high and the collector inlet was 15 cm from the surface. The chimney was constructed of a 12 m polyethylene tube with a diameter of 25 cm.

The solar collector was constructed of polycarbonate sheets. Polycarbonate sheets are mechanically strong, transparent, tough, heat resistant and fairly UV resistant. Two-layered PC sheets were selected to prevent heat loss and increase the greenhouse effect. Black material was used as the ground collector.

Figure 19 also shows various other experimental pilot plants that have been constructed as experimental sets (Dhahri and Omri, 2013).
Figure 18: Solar chimney experimental prototypes (Dhahri and Omri, 2013).

Figure 19: Pictures of experimental solar chimney sets (Dhahri and Omri, 2013).
2.8 Design of the system
A solar chimney is a power generating system that converts solar radiation into electricity, which is achieved by the flow of air through an elevated chimney, heated by solar energy or radiation from the sun. Heated air expands and rises, flowing through the chimney and escaping through the chimney outlet (Figure 20). Cooler air is drawn into the system through inlet apertures at the bottom of the structure. Suction of cooler air is enhanced by the air density difference between the ambient air and the heated air inside the chimney. The pressure difference created within the system drives the movement of cooler denser air from the outside through the apertures to the inside of the chimney.

The movement or flow of air is referred to as the thermal stack effect. Most solar chimney concepts focus on enhancing the thermal stack effect. The airflow in the system can be used to rotate a turbine and convert the kinetic energy of the air into electrical energy (Tan & Wong, 2014). In summary, electricity generation is achieved by combining three principles; namely, the greenhouse effect (the solar collector), the tower (the chimney) and the power conversion unit; e.g., a wind turbine or turbines (Zhou, Wang & Ochieng, 2010).

The advantages or benefits of a project like this are that this system does not consume water and there is no air pollution. The absence of fuel costs will protect the consumer from the fluctuating coal and oil prices; therefore, the operating costs of the solar chimney will be less. Employment will be created as there will be a necessity for qualified and skilled people to manufacture, construct, install and maintain the components and/or equipment of each solar chimney in operation. The area under the solar collector roof can be used to cultivate food, as it creates a “greenhouse effect”.

The disadvantages of this system are that it consumes large areas of space for the solar collector and must be constructed in areas with low township development potential. This means that the system is usually not constructed in close proximity to the areas where the electricity would be consumed. To be as efficient as possible, it must be constructed in regions with very consistent solar radiation throughout the
year. The system produces electricity predominantly during the day and energy storage interventions must be installed to ensure operation during night time.

Figure 20: Solar radiation creating air updraft in a chimney

2.9 Description of the system
A solar chimney power generation system consists of certain key sections to ensure successful operation. The selection of the materials for this project is governed by the significance of the required material properties. The properties of a material include the following:

- Mechanical properties: strength, density, stiffness, hardness, toughness, yield strength, fatigue strength, creep strength.
- Thermal properties: thermal conductivity and the specific heat capacity.
- Optical properties: transparency and clearness of the material.
- Surface properties: the ability of the material to withstand wear, abrasion and corrosion, and resistance to solvents.
- Aesthetic properties: the appearance of the material and its texture.

The costs of the materials depend on the processes and quantities used during the construction. The material costs and the cost of maintaining the structure during its life expectancy is considered during the selection process (Higgins, 2006).
These various parts (which are used to a larger or lesser extent) are described in the following sections and include: The Steel Plate (Base Plate) or collector, the Inlet aperture, the Chimney and the Turbine and Extension.

2.9.1 The Solar Collector or Base Plate
This is usually a major section of a solar chimney. The solar collector acts like a heat absorber that transforms the solar radiation from the sun into thermal energy. The solar collector is heated by the sun and heats air inside the chimney.

In larger systems the solar collector heats the air through the greenhouse effect. A transparent material, plastic film or a glass plastic film is commonly used for the roof of the solar collector. The roof is supported by a support matrix and pillar structure. The roof of the solar collector is placed a few metres above the ground and the height of the roof above the ground increases from the perimeter towards the base of the chimney (see Chapter 2, Literature review). This is done to divert the heated airflow to the chimney with the least friction loss (Zhou, Wang & Ochieng, 2010). Since the solar collector was not the focus in this study and design, the chimney is mounted on a base plate and acted as a small collector (Figure 21). This design does not make use of an energy storage system in the collector; although such a system is advocated by previous studies. The energy storage system is a thermal storage medium to store heat generated during the day for use at night (see Chapter 2, Literature study).

Solar collectors around an updraft chimney can consume a large area, depending on the desired power output. It is therefore advisable to investigate the shape that will yield the best possible use of space, while balancing it with the largest outside perimeter for the best possible airflow or mass flow volume. The concept that yields the largest outside perimeter will theoretically yield the best airflow efficiency, the largest airflow and the largest mass flow rate at a lower solar collector inlet height. Table 3 below compares variables calculated for a unit ground surface area (m$^2$) for various collector surface profile types.
This information will guide towards the profile with the optimum outside perimeter of the collector for the smallest construction, while maximum air flow rate is achieved. The advantage of achieving the optimum is that a higher solar chimney will be more efficient.

The profile that yields the largest outside perimeter is the triangular profile, second largest is the octagon, third the square and the circular profile yields the smallest perimeter. The comparison was based on a standardised area of one m$^2$ for all profiles, meaning that the amount of solar radiation received is the same. The circular profile yields the best use of area, and is thus the best choice for solar efficiency, but the worst for airflow.

Table 3: Solar collector surface profile types

<table>
<thead>
<tr>
<th>Surface profile</th>
<th>Ground surface area equation (m$^2$)</th>
<th>Perimeter equation</th>
<th>Perimeter value</th>
<th>Perimeter: Surface area ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Circle</td>
<td>$A = Br^2$</td>
<td>$2Br$</td>
<td>3.544 m</td>
<td>3.554: 1</td>
</tr>
<tr>
<td>Square</td>
<td>$s = \sqrt{x}$</td>
<td>4s</td>
<td>4.000 m</td>
<td>4 : 1</td>
</tr>
<tr>
<td>Octagon (8 triangles)</td>
<td>$b = \sqrt{\frac{x}{2\sqrt{3}\pi}}$</td>
<td>$8b$</td>
<td>4.298 m</td>
<td>4.298 : 1</td>
</tr>
<tr>
<td>Triangle (equal sides)</td>
<td>$b = \sqrt{\frac{4x}{\sqrt{3}\pi}}$</td>
<td>$3b$</td>
<td>4.559 m</td>
<td>4.559 : 1</td>
</tr>
</tbody>
</table>
The optimum profile is thus a compromise between the triangular and circular shape. The shape that was chosen for this study was the octagon (Figure 21) based on the near-optimal perimeter to surface ratio and the practical feasibility of the shape.

The following assumptions are generic to all of the considered shapes. The flow of air in the system through the collector and chimney; obey the Ideal Gas law:

$$P = \rho R_{air} T$$  \hspace{1cm} (2.1)

The mass flow through the control volume is steady and one-dimensional and the law for the conservation of mass is valid.

$$m_{inlet} = m_{outlet}$$  \hspace{1cm} (2.2)

### 2.9.2 The chimney

The chimney or the tower tube is the main attribute and is situated at the centre of the solar collector (Figure 21). The chimney acts as the engine of the apparatus by creating a temperature variation between the air situated at the top and the air situated at bottom. The temperature of the heated air at the bottom of the chimney is higher than the temperature of the air that has risen to the top, and this creates a phenomenon called the chimney effect. The chimney effect is the flow or sucking of air from the bottom at the chimney base to the top at the chimney outlet. Simulations of the effect of chimney height for cylindrical chimneys were investigated by Niemann, et, al., 2009. This research showed that larger air velocities are obtained by higher chimneys.

Positioning the turbine(s) at the chimney base simplifies the construction of the tower. The mass flow rate of the rising air is estimated to be directly and positively proportional to the solar collector temperature rise as well as the chimney height (Zhou, Wang & Ochieng, 2010).
2.9.3 The power conversion unit (turbines)

This section concerns the turbines for the solar chimney design. Choices to be considered in a full scale plant are the use of a vertical or horizontal shaft, single or multiple turbines, and with or without inlet guide vanes. Another possible choice is counter rotating turbines, with or without inlet guide vanes. The necessity of a diffuser or a guide cone in the centre of the tower is also considered.

Turbine(s) are arranged in the vertical shaft within the tower, whereas the horizontal arrangement is around the tower circumference. A vertical shaft arrangement minimises the cyclical stress, but a thrust bearing is required to carry the load of the entire turbine. A sealing of the horizontal to vertical flow change is essential for the horizontal shaft arrangement as the pressure after the turbine(s) section is sub-atmospheric (Fluri, 2008).
The advantage of single over multiple turbines is the simplicity of airflow and the small number of moving parts. The drawback of this; though, is that with larger Solar chimney designs; larger torque is needed, driving a single larger generator and this complicates manufacturing, handling and transportation (Fluri, 2008).

Inlet guide vanes reduce exit swirl of fluid or airflow. For small solar chimney designs this is not a necessity but with larger scale designs the exit swirl is significant. Exit swirl can also be decreased with counter rotating turbine(s) operating in the opposite direction of the first blade row, turning the flow back as close as possible to an axial flow direction (Fluri, 2008).

A diffuser is used to reduce exit kinetic losses in a multiple horizontal arrangement (Fluri, 2008). A guiding cone for this arrangement reduces losses by 43 per cent (Zhou, Wang & Ochieng, 2010).

However, the current development project is a small scale individual power generation unit. Therefore, the size of the chimney is small as the maximum height for the tower is 5 metres. Since the main aim of this study is to investigate the airflow in the chimney stack, only a single generator was mounted at the top of the stack (Figure 22), no inlet vanes are used and an outlet cone is installed at the top of the chimney (Figure 21).
2.9.4 Power storage

The output of large scale systems, such as at Manzanares in Spain, is usually directly fed into the national electricity network. If the output of a solar chimney plant is small, as in this case, the generated energy must be stored for later use. Batteries are usually the best choice. Various factors affect the choice and amount of batteries. A certain amount of batteries are usually needed to drive a specific size uninterrupted power supply (UPS) or inverter. Batteries can be classified into two groups, namely primary (non-rechargeable) batteries and secondary (rechargeable) batteries. Primary batteries are cheap, light in weight and are mostly used for portable electronic devices. Secondary batteries are used for electrical energy storage, are heavier and offer high discharge rates compared to primary or dry batteries. Secondary batteries can be lead-acid, lithium ion or nickel cadmium batteries (Solanki, 2009).
3 COMPARISON BETWEEN THE CONVENTIONAL DESIGN AND THE PROPOSED DESIGN

3.1 Concept selection for the Numerical Simulation

The decision making procedure to evaluate the concepts was based on using a decision or selection matrix (Table 4) to evaluate and prioritize a list of options. A list of weighted design criteria was established and each concept option evaluated against those criteria. This is an accepted procedure when a list of options must be narrowed to one or two choices; or when only one solution or problem-solving approach can be implemented.

Evaluation criteria appropriate to the project are brainstormed and an initial list of criteria is established. The initial list is usually broad and is subsequently reduced to the list of most important criteria of performance (30%), parts availability (25%), corrosion resistance and safety (15%), maintenance (10%) and cost (5%). A relative weight is assigned to each criterion; based on how important that criterion is to the successful implementation of the project. The sum of the relative weights of all listed criteria must be “1” or 100%.

An example of a matrix is given in Table 4. Usually, whichever of the criteria or concept options has fewer items determines the row labels. In this example the criteria and their weights are column labels and the list of concept options is row labels. Each concept option is evaluated against the criteria and rated on a scale of “1” to “10”; where “1” is completely unsuitable and “10” is perfectly suitable to satisfy the criterion.

Each option’s suitability rating is multiplied with the weight assigned to the design criterion. The results are summed for each individual option. The sum is the score for that particular option. The option with the highest score will not necessarily be chosen, but the relative scores can generate meaningful discussion and lead the project leader or the team towards a consensus decision.
Concept 1 is a cylindrical chimney, concept 2 an octagon chimney and concept 3 a triangular chimney. Concept 1 yielded a score of 8.7; concept 2 a score of 8.3 and concept 3 a score of 6.7. The concept with the highest score is Concept 1. The decision was to accept concept 2 because it suited our scientific aims better and scored only slightly less than concept 1.

Table 4: The decision matrix.

<table>
<thead>
<tr>
<th>Weighting factor</th>
<th>Safety</th>
<th>Maintenance</th>
<th>Cost</th>
<th>Performance resistant</th>
<th>Parts availability</th>
</tr>
</thead>
<tbody>
<tr>
<td>Concepts</td>
<td>0.15</td>
<td>0.1</td>
<td>0.05</td>
<td>0.3</td>
<td>0.15</td>
</tr>
<tr>
<td>Concept 1</td>
<td>9</td>
<td>1.35</td>
<td>9</td>
<td>0.9</td>
<td>9</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.35</td>
<td></td>
<td>0.35</td>
<td></td>
</tr>
<tr>
<td>Concept 2</td>
<td>8</td>
<td>1.2</td>
<td>7</td>
<td>0.7</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.45</td>
<td></td>
<td>0.45</td>
<td></td>
</tr>
<tr>
<td>Concept 3</td>
<td>8</td>
<td>1.2</td>
<td>6</td>
<td>0.6</td>
<td>7</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.6</td>
<td></td>
</tr>
</tbody>
</table>

3.2 Numerical Performance of Concepts

Numerical simulations are regularly performed (Deghani and Mohammadi, 2014) and two concepts were numerically simulated to evaluate the different factors that influence the performance of the solar updraft power plant. The concepts are:

- Cylindrical chimney and
- Octagon chimney with the inlet diameter larger than the output diameter.

The following parameters were evaluated for both concepts and will be discussed in more detail for each concept:

- Static air pressure
- Velocity of the air in the chimney
- Static air temperature
- Chimney height
- Inlet aperture of the chimney
3.2.1 Concept 1: Cylindrical Chimney

This concept is a collector sloping towards the chimney, with the height at the outlet of the solar collector (at the chimney) larger than at the inlet at the perimeter of the collector (Figure 23). Air heated in the collector decreases in density. This effect, coupled with the increased cross-sectional flow area at the outlet, results in an equal or slightly higher velocity at the exit of the collector compared with the velocity at the entrance of the collector.

Since the chimney cross-sectional flow area remains constant as the chimney height increases, the turbine was placed at the bottom inside the chimney.

![Figure 23: Sloped collector with cylindrical chimney.](image)

The mathematical model to describe and calculate the simulations of the chimney is discussed in chapter 4, using the boundary conditions in Table 6.

Table 5 shows the cylindrical chimney dimensions used during the simulations in ANSYS, the numerical flow simulation software. Note that the top and bottom diameters are the same and that the parameters are for a pilot plant.
Table 5: Cylindrical chimney dimensions used in ANSYS:

<table>
<thead>
<tr>
<th>Explanation</th>
<th>Physical dimensions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bottom diameter of the chimney</td>
<td>0.28 m</td>
</tr>
<tr>
<td>Top outlet diameter of the chimney</td>
<td>0.28 m</td>
</tr>
<tr>
<td>Height of the chimney</td>
<td>2.0 m</td>
</tr>
<tr>
<td>Inlet aperture</td>
<td>0.27 m</td>
</tr>
<tr>
<td>Collector diameter</td>
<td>4.00 m</td>
</tr>
<tr>
<td>Height of extension</td>
<td>0.57 m</td>
</tr>
<tr>
<td>Top diameter of extension</td>
<td>0.28 m</td>
</tr>
</tbody>
</table>

The simulations for the cylindrical plant (Figure 24) were performed using the input parameters given in Table 6.

Figure 24: Cylindrical chimney design used for simulations.

Table 6: Input parameters for the cylindrical chimney simulations

<table>
<thead>
<tr>
<th>Input parameters for numerical simulations – Cylindrical chimney</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ambient temperature</td>
</tr>
<tr>
<td>Collector Temperature</td>
</tr>
<tr>
<td>Pressure (Atmospheric)</td>
</tr>
</tbody>
</table>
Wind speed 0 m/s

<table>
<thead>
<tr>
<th>Materials</th>
<th>Steel and atmospheric air</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air density at 25°C</td>
<td>$\Delta = 1.183892 \text{ kg/m}^3$</td>
</tr>
</tbody>
</table>

Gravitational Acceleration

<table>
<thead>
<tr>
<th>X Axis</th>
<th>0 m/s$^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Y Axis</td>
<td>-9.81 m/s$^2$</td>
</tr>
<tr>
<td>Z Axis</td>
<td>0 m/s$^2$</td>
</tr>
</tbody>
</table>

The results for this simulation in ANSYS are given in Table 7 below. The simulations were performed by assigning simulation intervals commencing from the inlet aperture, throughout the length (height) of the chimney to the top of the extension. The values summarised in Table 7 are the simulation results on the inside of the solar power plant at the centre vertical axis of the chimney.

The intervals depicted in the first column of Table 7 are focused on three sections within the chimney. Section 1 is from 0.00 m to 0.27 m, and shows the values for the inlet aperture of the power plant. The intervals 0.27 m to 2.0 m classify the chimney and intervals 2.0 m to 2.5 m are the extension. Static air pressure as indicated in the table is the pressure difference obtained against atmospheric pressure. The area equation is from table 3 and air density from equation (2.1).

Table 7: Numerical modelling results for the cylindrical chimney

<table>
<thead>
<tr>
<th>Intervals</th>
<th>Area (m$^2$)</th>
<th>Air Density (kg/m$^3$)</th>
<th>Velocity (m/s)</th>
<th>Static Air Pressure (Pascal)</th>
<th>Static Air Temp (K)</th>
<th>Enthalpy (J/kg)</th>
<th>Kinetic Energy (J/kg)</th>
<th>Total Energy (J/kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.000</td>
<td>28.27</td>
<td>1.131</td>
<td>0.006</td>
<td>-0.03</td>
<td>312.19</td>
<td>2602.01</td>
<td>0.00</td>
<td>2602.01</td>
</tr>
<tr>
<td>0.135</td>
<td>8.34</td>
<td>1.138</td>
<td>0.226</td>
<td>0.00</td>
<td>310.09</td>
<td>25732.38</td>
<td>0.05</td>
<td>25732.43</td>
</tr>
<tr>
<td>0.270</td>
<td>0.06</td>
<td>1.140</td>
<td>0.742</td>
<td>-0.23</td>
<td>309.67</td>
<td>602.71</td>
<td>0.01</td>
<td>602.73</td>
</tr>
<tr>
<td>0.500</td>
<td>0.06</td>
<td>1.144</td>
<td>0.659</td>
<td>-0.43</td>
<td>308.47</td>
<td>481.40</td>
<td>0.01</td>
<td>481.41</td>
</tr>
<tr>
<td>0.750</td>
<td>0.06</td>
<td>1.145</td>
<td>0.696</td>
<td>-0.38</td>
<td>308.23</td>
<td>497.30</td>
<td>0.01</td>
<td>497.32</td>
</tr>
<tr>
<td>1.000</td>
<td>0.06</td>
<td>1.146</td>
<td>0.719</td>
<td>-0.35</td>
<td>308.03</td>
<td>503.37</td>
<td>0.01</td>
<td>503.38</td>
</tr>
<tr>
<td>1.500</td>
<td>0.06</td>
<td>1.148</td>
<td>0.716</td>
<td>-0.26</td>
<td>307.45</td>
<td>473.18</td>
<td>0.01</td>
<td>473.20</td>
</tr>
<tr>
<td>2.000</td>
<td>0.06</td>
<td>1.150</td>
<td>0.711</td>
<td>-0.16</td>
<td>306.99</td>
<td>447.25</td>
<td>0.01</td>
<td>447.26</td>
</tr>
<tr>
<td>2.250</td>
<td>0.06</td>
<td>1.151</td>
<td>0.706</td>
<td>-0.11</td>
<td>306.83</td>
<td>436.33</td>
<td>0.01</td>
<td>436.35</td>
</tr>
<tr>
<td>2.500</td>
<td>0.06</td>
<td>1.151</td>
<td>0.708</td>
<td>-0.06</td>
<td>306.71</td>
<td>431.52</td>
<td>0.01</td>
<td>431.54</td>
</tr>
</tbody>
</table>
The following sections will show the results for all the relevant physical entities which are important for the evaluation of the cylindrical solar plant.

### 3.2.1.1 Static air pressure results

Static air pressure is investigated to evaluate the airflow path inside the cylindrical chimney of the solar power plant. Differences in the static air pressure at different intervals throughout the chimney create a positive static air pressure and create the updraft. The updraft result in the movement of air from the inlet aperture upwards through the chimney to turn the turbine mounted at the base of the chimney.

The simulation results obtained with the ANSYS software of the variations of the static pressure are shown in Figure 25.

![Cylindrical Chimney - Static Air Pressure](image)

Figure 25: Static air pressure variation inside the cylindrical chimney.

Figure 25 shows the association between static air pressures at defined intervals within the cylindrical chimney. The shape of the figure indicates that the maximum flue pressure is at the bottom just above the inlet and decreases with height in the chimney. The flue pressure approaches the smallest value (close to the atmospheric pressure) at the outlet (2.5 m). This static air pressure graph indicates that the best position for the turbine is at the bottom of the chimney.
3.2.1.2 Velocity results (Y-Direction upwards)

The vertical velocity of the air flow inside the flue is created by the rate at which the air flows into the chimney of the pilot plant through the inlet aperture at the bottom. The velocity inside the solar power plant is determined by the rate of change of the vertical movement of the air at a specific position inside the chimney. The simulated velocities are presented in Figure 26 at defined intervals within the chimney.

Figure 26 indicates that the velocity increases sharply at the base of the chimney just above the inlet. It then stabilises to a lower value throughout the chimney, which confirms that the best position of the turbine is at the bottom of the chimney. However, the constant velocity throughout the chimney indicates that the turbine can be positioned at any height within the chimney, if it is preferred not to place the turbine at the bottom.

![Cylindrical Chimney - Velocity](image)

Figure 26: Velocity variation inside the cylindrical chimney.

3.2.1.3 Static air temperature (Kelvin)

The static air temperature of the air inside the chimney is due to the heat absorbed from the solar radiation of the sun by the collector of which the chimney is constructed. As a result, the hot air is less dense and is flowing upwards through the solar power plant.
The simulations confirm that the largest static air temperature is obtained at the bottom of the chimney close to the inlet. The static air temperature of the air in the chimney then lowers as air ascends through the chimney. At the outlet of the chimney the static air temperature approaches the ambient temperature. The simulated static air temperatures are presented in Figure 27.

Figure 27: Static air temperature variation inside the cylindrical chimney.

### 3.2.1.4 Air density

The heating of air inside and at the bottom of a chimney causes the lowering of the air density at the inside and at the bottom of the chimney. Lowering of the density causes this air layer to rise towards the top and is one of the causes of the chimney updraft. Air density variations in the power plant are associated with variations of temperature throughout the chimney.

The simulations in ANSYS (Figure 28) show the density variations through the cylindrical chimney. The lowest densities are obtained at the inlet of the chimney due to the fact that the temperature transfer to the air increases the temperature and thus lowers the density.
The behaviour of the density distribution through the chimney should be viewed in conjunction with Figure 27, which depicts the temperature distribution through the chimney. The lowest air densities are directly associated with the largest temperatures in the chimney. The air density increase slightly through the solar chimney upwards as the temperature decreases. The same association is also applicable to the air density and the pressure inside the chimney (Figure 25), although not as profound.

Figure 28 shows that air density initially increases fairly sharply at the inlet section of the chimney and after the initial increase continues to slowly increase upwards through the chimney towards the outlet.

![Cylindrical Chimney - Air Density](image)

Figure 28: Air density variation inside the cylindrical chimney.

### 3.2.1.5 Simulations with different parameters

Simulations were performed for the cylindrical chimney design to evaluate the influence of different parameters on the performance of the chimney. The parameters evaluated were changed one at a time to evaluate the effect. The following sections describe the parameters that were evaluated.
### 3.2.1.6 Chimney height versus air velocity

The influence of the chimney height on the air velocity was evaluated. During these simulations only the height of the chimney and ambient temperature were changed and all the other parameters were kept fixed.

The air velocities were obtained for three different chimney heights and for three different ambient temperatures. The results of these simulations are shown in Table 8. The velocity was calculated at the bottom of the chimney close to the inlet where the turbine will be placed.

Table 8: Simulation results of cylindrical chimney height versus velocity

<table>
<thead>
<tr>
<th>Chimney height (m)</th>
<th>Ambient temperature °C</th>
<th>17 °C</th>
<th>25 °C</th>
<th>38 °C</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.574</td>
<td>0.645</td>
<td>0.700</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>0.728</td>
<td>0.783</td>
<td>0.851</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>0.762</td>
<td>0.857</td>
<td>0.950</td>
<td></td>
</tr>
</tbody>
</table>

The results are also shown graphically in Figure 29. As expected, the graph shows that the air velocity increases when the height of the chimney increases at constant temperatures. The velocity also increases with an increase in temperature.

![Cylindrical Chimney Height versus Velocity](image)

**Figure 29:** Chimney height versus air velocity for the cylindrical chimney.
3.2.1.7 Chimney height versus static air pressure

The influence of the chimney height on the static air pressure was the next parameter evaluated. During these simulations only the height of the chimney and ambient temperature were changed and all the other parameters were kept fixed.

The static air pressures were obtained for three different chimney heights and for three different ambient temperatures. The results of these simulations are shown in Table 9. The static air pressure was calculated from air pressure measured at the bottom of the chimney close to the inlet where the turbine will be placed, and at the top of the chimney, close to the outlet:

\[ \Delta P = P_{\text{inlet}} - P_{\text{outlet}} \] (3.1)

Table 9: Simulation results of cylindrical chimney height versus static air pressure.

<table>
<thead>
<tr>
<th>Chimney height (m)</th>
<th>Ambient temperature °C</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>17 °C</td>
<td>25 °C</td>
<td>38 °C</td>
</tr>
<tr>
<td>1</td>
<td>-0.043</td>
<td>-0.07</td>
<td>-0.173</td>
</tr>
<tr>
<td>2</td>
<td>-0.132</td>
<td>-0.175</td>
<td>-0.350</td>
</tr>
<tr>
<td>3</td>
<td>-0.185</td>
<td>-0.253</td>
<td>-0.461</td>
</tr>
</tbody>
</table>

The results are also shown graphically in Figure 30. As expected, the graph shows that the static air pressures increases when the height of the chimney increases at constant temperatures. The static air pressures also increases with an increase in temperature.
3.2.1.8 Chimney height versus static air temperature

The influence of the chimney height on the differences in static air temperatures was also evaluated. During these simulations only the height of the chimney and ambient temperature were changed and all the other parameters were kept fixed.

The static air temperatures were obtained for three different chimney heights and for three different ambient temperatures. The results of these simulations are shown in Table 10. The static air temperatures were calculated from the temperatures measured at the bottom of the chimney close to the inlet where the turbine will be placed, and at the top of the chimney near the outlet:

\[ \Delta T = T_{\text{inlet}} - T_{\text{outlet}} \]  

(3.2)
Table 10: Simulation results of cylindrical chimney height versus static air temperature.

<table>
<thead>
<tr>
<th>Chimney height (m)</th>
<th>Ambient temperature °C</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>17°C</td>
</tr>
<tr>
<td>1</td>
<td>0.385</td>
</tr>
<tr>
<td>2</td>
<td>0.250</td>
</tr>
<tr>
<td>3</td>
<td>0.001</td>
</tr>
</tbody>
</table>

The results are also shown graphically in Figure 31. As expected, the graph shows that the static air temperature increases when the height of the chimney increases at constant temperatures. It shows also that for low temperatures, the temperature close to the collector is higher than ambient temperature, and that it cools down quickly towards the top. Low temperatures would not be able to establish a chimney effect if the chimney is higher and if a larger collector should be used.

![Cylindrical Chimney Height versus Static Air Temperature changes](image_url)

Figure 31: Chimney height versus static air temperature changes for the cylindrical chimney.
3.2.1.9 Inlet aperture versus air velocity

The influence of the chimney inlet aperture versus the air velocity was investigated. During these simulations only the height of the inlet aperture and ambient temperature were changed and all the other parameters were kept fixed according to the values in Table 6.

The air velocities inside the chimney were obtained for four different inlet aperture heights and for three different ambient temperatures. The results of these simulations are shown in Table 11. The velocities were measured at the bottom of the chimney close to the inlet where the turbine will be placed.

Table 11: Simulation results of cylindrical chimney inlet aperture height versus velocity.

<table>
<thead>
<tr>
<th>Aperture height (m)</th>
<th>Ambient temperature °C</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>17 °C</td>
<td>25 °C</td>
<td>38 °C</td>
<td></td>
</tr>
<tr>
<td>0.15</td>
<td>0.717</td>
<td>0.807</td>
<td>0.860</td>
<td></td>
</tr>
<tr>
<td>0.20</td>
<td>0.721</td>
<td>0.804</td>
<td>0.856</td>
<td></td>
</tr>
<tr>
<td>0.27</td>
<td>0.738</td>
<td>0.793</td>
<td>0.841</td>
<td></td>
</tr>
<tr>
<td>0.32</td>
<td>0.739</td>
<td>0.781</td>
<td>0.836</td>
<td></td>
</tr>
</tbody>
</table>

Figure 32: Inlet aperture height versus velocity for the cylindrical chimney.
Figure 32 shows that for each temperature there is an optimum inlet aperture. The velocities are higher at higher temperatures, as to be expected. A solar plant will experience different temperatures during the day and the performance of the power plant must be as steady as possible. The graph shows that for this chimney height (2.0 m) the velocities tend to converge at an inlet aperture of 0.3 m, which indicates the optimum inlet aperture at a large range of temperatures.

3.2.1.10 Inlet aperture versus static air pressure changes

The influence of the chimney inlet aperture versus the static air pressure was investigated since pressure changes drive the chimney effect. During these simulations only the height of the inlet aperture and ambient temperature were changed and all the other parameters were kept fixed as given in Table 6.

The static air pressure differences were obtained for four different inlet apertures and for three different ambient temperatures. The results of these simulations are shown in Table 12. The static air pressure was calculated with equation (3.1) from the air pressure measured at the bottom of the chimney close to the inlet where the turbine will be placed, and at the top of the chimney, close to the outlet:

The static air pressure differences were obtained for four different inlet apertures and for three different ambient temperatures. The results of these simulations are shown in Table 12. The static air pressure was calculated with equation (3.1) from the air pressure measured at the bottom of the chimney close to the inlet where the turbine will be placed, and at the top of the chimney, close to the outlet:

<table>
<thead>
<tr>
<th>Cylindrical chimney: Inlet aperture versus Static air pressure changes</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Aperture height (m)</strong></td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>0.15</td>
</tr>
<tr>
<td>0.20</td>
</tr>
<tr>
<td>0.27</td>
</tr>
<tr>
<td>0.32</td>
</tr>
</tbody>
</table>

Figure 33 shows that for each temperature the optimum inlet aperture is at 0.27 m, where the pressure differences are the largest. The static air pressures are also larger at higher temperatures, as to be expected. A solar plant will experience different temperatures during the day and the performance of the power plant must be as steady as possible. The graph shows that for this chimney height (2m) the
pressures tend to converge at an inlet aperture of 0.27 m, which indicates the optimum inlet aperture at a large range of temperatures.

![Cylindrical Chimney Inlet Aperture versus Static Air Pressure changes](image)

Figure 33: Inlet aperture height versus static air pressure for the cylindrical chimney.

### 3.2.1.11 Inlet aperture versus static air temperature

The influence of the chimney inlet aperture versus the static air temperature was investigated due to the fact that temperature changes also drive the chimney effect. During these simulations only the height of the inlet aperture and ambient temperature were changed and all the other parameters were kept fixed.

The static air temperature differences were obtained for four different inlet apertures and for three different ambient temperatures. The results of these simulations are shown in Table 13. The static air temperatures were calculated using equation (3.2), from air temperatures measured at the bottom of the chimney close to the inlet where the turbine will be placed, and temperatures at the top of the chimney.

Table 13: Simulation results of cylindrical chimney inlet aperture height versus static air temperature in Kelvin.
Figure 34: Inlet aperture height versus static air temperature for the cylindrical chimney.

Figure 34 shows the influence of the inlet aperture height on the static air temperature at various ambient temperatures. The graph shows that for this chimney height (2 m) the static air temperatures are at a maximum with a chimney inlet aperture of 0.27 m, regardless of the ambient temperature. The static air temperatures are also higher at higher temperatures, as to be expected. Finding the optimum aperture height at a range of ambient air temperatures is required because...
a solar plant will be subjected to different temperatures during the day and the performance of the power plant must be as consistent as possible.

### 3.2.2 Concept 2: Octagon Conical Chimney

This concept is a sloping collector towards the chimney, with the height at the outlet of the solar collector (at the chimney) larger than at the inlet at the perimeter of the collector (Figure 35). Air heated in the collector decreases in density. This effect, coupled with the increased cross-sectional flow area at the outlet, results in an equal or slightly higher velocity at the exit of the collector compared with the velocity at the entrance of the collector. Since the chimney cross-sectional flow area does not remain constant as the chimney height increases, it acts like a venturi and the turbine must be placed close to the outlet at the top inside the chimney.

![Figure 35: Inlet aperture height versus static temperature for the cylindrical chimney.](image)

Table 14 shows the parameters that were used during the simulations in ANSYS. Note that the top and bottom diameters are not same and that the parameters are for a pilot plant.

<table>
<thead>
<tr>
<th>Explanation</th>
<th>Physical dimensions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bottom diameter of the chimney</td>
<td>2.4 m</td>
</tr>
<tr>
<td>Top outlet diameter of the chimney</td>
<td>0.28 m</td>
</tr>
<tr>
<td>Height of the chimney</td>
<td>2.0 m</td>
</tr>
</tbody>
</table>
The mathematical model to describe and calculate the simulations of the chimney (Figure 35) is discussed in chapter 4, using the boundary conditions in table 6.

The results for this simulation in ANSYS are given in Table 15 below. The simulations were performed by assigning simulation intervals that commenced from the inlet aperture, through the length (height) of the chimney till the top of the extension. The values summarised in Table 15 are the simulation results on the inside of the solar power plant at the centre vertical axis of the chimney. Static air pressure as indicated in the table is the pressure difference obtained against atmospheric pressure. The area equation is from table 3 and air density from equation (2.1).

Table 15: Simulation results for Concept Two.

<table>
<thead>
<tr>
<th>Interval</th>
<th>Area (m²)</th>
<th>Air Density (kg/m³)</th>
<th>Velocity (m/s)</th>
<th>Static Air Pressure (Pascal)</th>
<th>Static Air Temp (K)</th>
<th>Enthalpy (J/kg)</th>
<th>Kinetic Energy (J/kg)</th>
<th>Total Energy (J/kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>-0.20</td>
<td>1.16</td>
<td>1.15</td>
<td>1.19</td>
<td>-0.16</td>
<td>306.43</td>
<td>13239.81</td>
<td>1.13</td>
<td>13240.93</td>
</tr>
<tr>
<td>0.00</td>
<td>1.16</td>
<td>1.17</td>
<td>1.25</td>
<td>-0.14</td>
<td>301.67</td>
<td>5997.39</td>
<td>1.33</td>
<td>5998.71</td>
</tr>
<tr>
<td>0.30</td>
<td>0.94</td>
<td>1.18</td>
<td>0.55</td>
<td>-0.14</td>
<td>300.10</td>
<td>1192.06</td>
<td>0.09</td>
<td>1192.15</td>
</tr>
<tr>
<td>0.60</td>
<td>0.74</td>
<td>1.18</td>
<td>0.70</td>
<td>-0.13</td>
<td>300.05</td>
<td>1165.72</td>
<td>0.15</td>
<td>1165.87</td>
</tr>
<tr>
<td>0.90</td>
<td>0.56</td>
<td>1.18</td>
<td>0.95</td>
<td>-0.10</td>
<td>300.21</td>
<td>1293.39</td>
<td>0.28</td>
<td>1293.67</td>
</tr>
<tr>
<td>1.20</td>
<td>0.41</td>
<td>1.17</td>
<td>1.04</td>
<td>-0.05</td>
<td>300.49</td>
<td>1179.42</td>
<td>0.27</td>
<td>1179.69</td>
</tr>
<tr>
<td>1.50</td>
<td>0.28</td>
<td>1.17</td>
<td>1.27</td>
<td>-0.01</td>
<td>301.03</td>
<td>1208.22</td>
<td>0.34</td>
<td>1208.56</td>
</tr>
<tr>
<td>1.80</td>
<td>0.18</td>
<td>1.17</td>
<td>1.74</td>
<td>-0.04</td>
<td>301.68</td>
<td>1300.03</td>
<td>0.55</td>
<td>1300.59</td>
</tr>
<tr>
<td>2.00</td>
<td>0.12</td>
<td>1.17</td>
<td>2.40</td>
<td>0.04</td>
<td>302.23</td>
<td>1380.82</td>
<td>0.97</td>
<td>1381.79</td>
</tr>
<tr>
<td>2.30</td>
<td>0.17</td>
<td>1.18</td>
<td>0.06</td>
<td>0.04</td>
<td>298.15</td>
<td>0.02</td>
<td>0.00</td>
<td>0.02</td>
</tr>
<tr>
<td>2.60</td>
<td>0.18</td>
<td>1.18</td>
<td>0.08</td>
<td>0.03</td>
<td>298.15</td>
<td>0.08</td>
<td>0.00</td>
<td>0.08</td>
</tr>
<tr>
<td>2.90</td>
<td>0.21</td>
<td>1.18</td>
<td>0.14</td>
<td>-0.03</td>
<td>298.16</td>
<td>0.28</td>
<td>0.00</td>
<td>0.28</td>
</tr>
<tr>
<td>3.20</td>
<td>0.24</td>
<td>1.18</td>
<td>0.30</td>
<td>0.02</td>
<td>298.16</td>
<td>0.92</td>
<td>0.00</td>
<td>0.92</td>
</tr>
</tbody>
</table>

The intervals depicted in the first column of Table 15, focus on three (3) sections within the chimney. Section 1 is from -0.2 m to 0.00 m, and shows the values for the inlet aperture of the power plant. The intervals 0.0 m to 2.0 m classify the chimney...
and intervals 2.0 m to 3.2 m are the extension. The following sections will show the results for all the relevant physical entities which are important for the evaluation of the solar plant.

### 3.2.2.1 Static Air Pressure

Static air pressure is investigated to evaluate the airflow path inside the chimney of the solar power plant. Differences in the static air pressure at height through the chimney create a positive static air pressure and create the updraft; resulting in the movement of air upwards through the chimney of solar power plant from the inlet aperture to turn the turbine mounted at the outlet of the chimney. The simulation results obtained with the ANSYS software of the variations of the static air pressure are shown in Figure 36.

Figure 36 shows very clearly that the static air pressure gradient is the largest negative at the bottom of the chimney and decreases steadily throughout the chimney towards the top. The pressure at the bottom in the chimney flue is lower (the lowest) than the ambient pressure, which creates the draft. The pressure gradient decreases through the output and extension again as the energy source is removed.

![Octagon Chimney - Static Pressure](Image)

**Figure 36:** Simulated static air pressure in the flue of the octagon chimney.
It also shows the association between static air pressures at defined height intervals within the chimney. The figure indicates that the flue pressure increases with height in the chimney and approaches the largest value at the outlet (2 m). The pressure then lowers towards the ambient value in the extension, and reduces and oscillates close to ambient pressure after it passed through the venturi tube.

### 3.2.2.2 Velocity in Y direction (upwards)

The vertical velocity of the air flow inside the flue is created by the rate at which the air flows into the chimney of the power plant through the inlet aperture at the bottom. The velocity inside the solar power plant is determined by the rate of change of the vertical movement of the air at a specific position inside the chimney. The simulated velocity differences are presented in Figure 37.

![Octagon Chimney - Velocity (Y-Direction)](image)

**Figure 37:** Simulated vertical air velocity in the flue of the octagon chimney.

Figure 37 shows that the velocity is the lowest at the bottom of the chimney. The figure shows that the air accelerates against gravity and the velocity increases from the inlet vertical in the flue to turn the turbine at the top of the chimney, where the air velocity is the largest. The velocity approaches a maximum value at the outlet into the extension and decreases very rapidly.
3.2.2.3 Static Air Temperature (Kelvin)

The static air temperature of the air inside the chimney is due to the heat absorbed from the solar radiation of the sun by the steel plates of which the chimney is manufactured. As a result, the warmer air is flowing through the solar power plant. The simulated static air temperatures are presented in Figure 38.

![Octagon Chimney - Static Temperature](image)

Figure 38: Simulated static air temperature in the flue of the octagon chimney.

Figure 38 shows that the temperature is the largest at the bottom of the chimney. This is due to the fact that the collector also absorbs heat from the solar radiation and stimulates the flow of hot air through the solar power plant. The static air temperature first decreases sharply as it enters the chimney and increases steadily upwards towards the outlet of the chimney at 2 m. It then decreases sharply into the extension towards the atmosphere. After the outlet it decreases sharply and stabilises to be equal to the ambient temperature.

3.2.2.4 Air Density

The heating of air inside and at the bottom of a chimney causes the lowering of the air density at the bottom. The lowering of the air density at the inside and at the bottom of the chimney causes this air to rise towards the top and is one of the causes for the chimney updraft. Air density variations in the power plant are associated with variations of temperature throughout the chimney.
The simulation (Figure 39) shows the density variations through the chimney. The behaviour of the density distribution through the chimney should be viewed in conjunction with Figure 38, which depicts the temperature distribution through the chimney. The lowest air densities are directly associated with the highest temperatures in the chimney. The air densities also increase slightly through the solar chimney upwards as the temperature decreases.

![Octagon Chimney - Air Density](image)

Figure 39: Simulated air densities in the flue of the octagon chimney.

Figure 39 shows that air density initially increases slightly at the inlet and slowly decreases upwards through the chimney towards the outlet at 2 m. The air density then slight increases as expected after the outlet at 2 m into the extension, due to the fact that the air pressure is now at ambient pressure and temperature. After that it stabilises to reach the ambient air density.

### 3.2.2.5 Simulations with different parameters

Simulations were performed for the octagon chimney design to evaluate the influence of different parameters on the performance of the octagon chimney. The parameters evaluated were changed one at a time to evaluate the effect. The following sections describe the parameters that were evaluated.
3.2.2.6 Chimney height versus velocity

The influence of the chimney height on the air velocity was evaluated. During these simulations only the height of the chimney and ambient temperature were changed and all the other parameters were kept fixed as given in Table 6.

The air velocities were obtained for five different chimney heights and for three different ambient temperatures. The results of these simulations are shown in Table 16. The velocity was measured at the top of the chimney close to the outlet where the turbine will be placed.

Table 16: Simulation results of octagon chimney height versus velocity

<table>
<thead>
<tr>
<th>Chimney height (m)</th>
<th>Ambient Temperature °C</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>17 °C</td>
</tr>
<tr>
<td>1</td>
<td>0.994</td>
</tr>
<tr>
<td>1.5</td>
<td>0.991</td>
</tr>
<tr>
<td>2</td>
<td>1.767</td>
</tr>
<tr>
<td>2.7</td>
<td>1.628</td>
</tr>
<tr>
<td>3</td>
<td>1.421</td>
</tr>
</tbody>
</table>

The results are also shown graphically in Figure 40.

Figure 40: Chimney height versus air velocity for the octagon chimney.
As expected, the graph shows that the air velocity at the outlet increases when the height of the chimney increases at constant temperatures. The velocity also increases with an increase in temperature.

### 3.2.2.7 Chimney height versus static air pressure

The influence of the chimney height on the static air pressure was the next parameter evaluated. During these simulations only the height of the chimney and ambient temperature were changed and all the other parameters were kept fixed.

The static air pressures were obtained for five different chimney heights and for three different ambient temperatures. The results of these simulations are shown in Table 17. The air pressures were measured at the bottom (inlet aperture) and top of the chimney close to the outlet where the turbine will be placed, and the static air pressures were calculated using equation (3.1)

<table>
<thead>
<tr>
<th>Octagon chimney results: Chimney height versus static air pressure changes</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Chimney height (m)</strong></td>
</tr>
<tr>
<td>1</td>
</tr>
<tr>
<td>1.5</td>
</tr>
<tr>
<td>2</td>
</tr>
<tr>
<td>2.7</td>
</tr>
<tr>
<td>3</td>
</tr>
</tbody>
</table>

The results are also shown graphically in Figure 41. As expected, the graph shows that the static air pressures increases when the height of the chimney increases at constant temperatures. The static air pressures also increases with an increase in temperature. The maximum static pressures are simulated for a wide range of temperatures, and indicate the optimum chimney height of 2 m for these parameters.
3.2.2.8 Chimney height versus static air temperature changes

The influence of the chimney height on the differences in static air temperatures was also evaluated. During these simulations only the height of the chimney and ambient temperature were changed and all the other parameters were kept fixed.

The static air temperatures were obtained for five different chimney heights and for three different ambient temperatures. The results of these simulations are shown in Table 18. The static air temperatures were measured at the bottom (inlet aperture) and top of the chimney close to the outlet where the turbine will be placed, and was calculated using equation (3.2).

Table 18: Simulation results of octagon chimney height versus static air temperature.

<table>
<thead>
<tr>
<th>Octagon chimney: Chimney height versus static air temperature</th>
<th>Ambient temperature °C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chimney height (m)</td>
<td>17 °C</td>
</tr>
<tr>
<td>1</td>
<td>1.356</td>
</tr>
<tr>
<td>1.5</td>
<td>1.164</td>
</tr>
<tr>
<td>2</td>
<td>1.099</td>
</tr>
<tr>
<td>2.7</td>
<td>1.062</td>
</tr>
<tr>
<td>3</td>
<td>1.016</td>
</tr>
</tbody>
</table>
The results are also shown graphically in Figure 42. As expected, the graph shows that the static air temperature increases when the height of the chimney increases at constant temperatures. It shows also that for low temperatures, the temperature close to the collector is larger than ambient temperature, and that it cools down quickly towards the top. Low temperatures would not establish a chimney effect if the chimney is higher and a larger collector should be used.

![Octagon Chimney - Height versus Static Air Temperature Changes](image_url)

Figure 42: Chimney height versus static air temperature changes for the octagon chimney.

### 3.2.2.9 Inlet aperture versus velocity

The influence of the chimney inlet aperture versus the velocity was investigated. During these simulations only the height of the inlet aperture and ambient temperature were changed and all the other parameters were kept fixed as in Table 6.

The velocities inside the chimney were obtained for five different inlet apertures and for three different ambient temperatures. The results of these simulations are shown in Table 19. The velocities were measured at the top of the chimney close to the outlet where the turbine will be placed.
Table 19: Simulation results of cylindrical chimney inlet aperture height versus velocity.

<table>
<thead>
<tr>
<th>Octagon chimney results: Inlet aperture versus velocity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aperture height (m)</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>---------------------</td>
</tr>
<tr>
<td>0.15</td>
</tr>
<tr>
<td>0.2</td>
</tr>
<tr>
<td>0.27</td>
</tr>
<tr>
<td>0.32</td>
</tr>
<tr>
<td>0.4</td>
</tr>
</tbody>
</table>

Figure 43: Inlet aperture height versus velocity for the octagon chimney.

Figure 43 shows that for each temperature there is an optimum inlet aperture. The velocities are higher at higher temperatures, as to be expected. A solar plant will be submitted to different ambient temperatures during the day and the performance of the power plant must be as constant as possible. The graph shows that for this chimney height (given in Table 19) the velocities tend to converge at an inlet aperture of 0.27 m, which indicates the optimum inlet aperture at a large range of ambient temperatures.
3.2.2.10 Inlet aperture versus static air pressure changes

The influence of the chimney inlet aperture versus the static air pressure was investigated due to the fact that pressure changes drive the chimney effect. During these simulations only the height of the inlet aperture and ambient temperature were changed and all the other parameters were kept fixed as in Table 14.

The static air pressure differences were obtained for five different inlet apertures and for three different ambient temperatures. The results of these simulations are shown in Table 20. The air pressures were measured at the bottom (inlet aperture) and top of the chimney close to the outlet where the turbine will be placed, and the static air pressure was calculated using equation (3.1).

Table 20: Simulation results of octagon chimney inlet aperture height versus static air pressure.

<table>
<thead>
<tr>
<th>Octagon chimney: Inlet aperture versus static air pressure</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aperture height (m)</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>0.15</td>
</tr>
<tr>
<td>0.2</td>
</tr>
<tr>
<td>0.27</td>
</tr>
<tr>
<td>0.32</td>
</tr>
<tr>
<td>0.4</td>
</tr>
</tbody>
</table>

Figure 4 shows that for each temperature the optimum inlet aperture is at 0.27 m, where the pressure differences are the largest. The pressure differences are also larger at higher temperatures, as to be expected. A solar plant will be subject to different temperatures during the day and the performance of the power plant must be as constant as possible. The graph shows that for this chimney height the static pressures tend to converge at an inlet aperture of 0.27 m, which indicates the optimum inlet aperture at a large range of temperatures.
3.2.2.11 Inlet aperture versus static air temperature

The influence of the chimney inlet aperture versus the static air temperature was investigated since temperature changes also drive the chimney effect. During these simulations only the height of the inlet aperture and ambient temperature were changed and all the other parameters were kept fixed as in Table 14. The static temperature differences were obtained for five different inlet apertures and for three different ambient temperatures. The results of these simulations are shown in Table 21. The air temperatures were measured at the bottom (inlet aperture) and top of the chimney close to the outlet where the turbine will be placed, and the static air temperature was calculated using equation (3.2).

Table 21: Simulation results of octagon chimney inlet aperture height versus static air temperature in Kelvin.

<table>
<thead>
<tr>
<th>Octagon chimney: Inlet aperture versus static air temperature</th>
<th>Ambient Temperature °C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aperture Height (m)</td>
<td>17 °C</td>
</tr>
<tr>
<td>---------------------</td>
<td>-------</td>
</tr>
<tr>
<td>0.15</td>
<td>2.144</td>
</tr>
<tr>
<td>0.2</td>
<td>1.530</td>
</tr>
<tr>
<td>0.27</td>
<td>1.500</td>
</tr>
<tr>
<td>0.32</td>
<td>0.999</td>
</tr>
<tr>
<td>0.4</td>
<td>0.524</td>
</tr>
</tbody>
</table>
Figure 45: Inlet aperture height versus static air temperature for the octagon chimney.

A solar plant will experience different ambient temperatures during the day and the performance of the power plant must be as constant as possible. Considering this, the optimum aperture is not only the aperture yielding the highest static temperature, which, in this case, was an inlet of 0.15 m. The optimum aperture is the aperture yielding the highest static temperature, but with the least variation in static temperature over a range of ambient temperatures. Based on these criteria, Figure 45 shows that for these simulation parameters the optimum inlet aperture is 0.27 m, regardless of the ambient temperature. The static air temperatures are also larger at higher ambient temperatures, as to be expected. The graph shows that for this chimney height the static temperatures are at an optimum with a chimney inlet aperture of 0.27 m, which indicates the optimum inlet aperture at a large range of temperatures.

3.2.2.12 Chimney bottom radius versus velocity

The influence of the bottom chimney radius versus the air velocity inside the chimney was investigated since this radius also drives the chimney effect. During these simulations only the bottom radius and ambient temperature were changed and all the other parameters were kept fixed. The best velocities for this plant were obtained for five different bottom radii and for three different ambient temperatures. The results of these simulations are shown in Table 22.
Table 22: Simulation results of octagon chimney bottom chimney radius and ambient temperature versus velocity.

<table>
<thead>
<tr>
<th>Bottom radius (m)</th>
<th>Ambient temperature °C</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>17 °C</td>
</tr>
<tr>
<td>0.3</td>
<td>1.362</td>
</tr>
<tr>
<td>0.7</td>
<td>1.010</td>
</tr>
<tr>
<td>1.2</td>
<td>1.683</td>
</tr>
<tr>
<td>1.5</td>
<td>0.969</td>
</tr>
<tr>
<td>2</td>
<td>1.549</td>
</tr>
</tbody>
</table>

Figure 46 shows that for these simulation parameters the velocity is at the optimum with a bottom radius of 1.2 m. The velocities are also larger at higher temperatures, as to be expected. A solar plant is subject to different ambient temperatures during the day and the performance of the power plant must be as constant as possible. The graph shows that for this chimney height (according to Table 22) the bottom radius is at an optimum with a value of 1.2 m, which indicates the optimum bottom radius at a large range of ambient temperatures.

Figure 46: Bottom radius versus velocity for the octagon chimney.
3.2.2.13 Chimney bottom radius versus static air pressure

The influence of the bottom chimney radius versus the static air pressure inside the chimney was investigated since this radius also drives the pressure and the chimney effect. During these simulations only the bottom radius and ambient temperature were changed and all the other parameters were kept fixed as in Table 14. The best static air pressure changes for this plant were obtained for five different bottom radii and for three different ambient temperatures. The results of these simulations are shown in Table 23. The air pressures were measured at the bottom (inlet aperture) and top of the chimney close to the outlet where the turbine will be placed, and the static air pressure was calculated using equation (3.1).

Table 23: Simulation results of octagon chimney bottom chimney radius versus static air pressure.

<table>
<thead>
<tr>
<th>Octagon chimney: Bottom radius versus static air pressure</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Bottom radius (m)</strong></td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>0.3</td>
</tr>
<tr>
<td>0.7</td>
</tr>
<tr>
<td>1.2</td>
</tr>
<tr>
<td>1.5</td>
</tr>
<tr>
<td>2</td>
</tr>
</tbody>
</table>

Figure 47: Bottom radius versus static air pressure for the octagon chimney.
Figure 47 shows that for these simulation parameters the static air pressure difference is at the optimum with a bottom radius of 1.2 m, regardless of the ambient temperature. The static air pressures are also larger at higher temperatures, as to be expected. A solar plant will be subject to different ambient temperatures during the day and the performance of the power plant must be as constant as possible. The graph shows that for this chimney height (2 m) the bottom radius is at an optimum at 1.2 m.

3.2.2.14 Chimney bottom radius versus static air temperature

The influence of the bottom chimney radius versus the static air temperature inside the chimney was investigated. During these simulations only the bottom radius and ambient temperature were changed and all the other parameters were kept fixed as in Table 14. The best static air temperature changes for this plant were obtained for five different bottom radii and for three different ambient temperatures. The results of these simulations are shown in Table 24. The air temperatures were measured at the bottom (inlet aperture) and top of the chimney close to the outlet where the turbine will be placed, and the static air temperature was calculated using equation (3.2).

Table 24: Simulation results of octagon chimney bottom chimney radius versus static air temperature.

<table>
<thead>
<tr>
<th>Octagon chimney: Bottom radius versus static air temperature</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bottom radius (m)</td>
</tr>
<tr>
<td>-------------------</td>
</tr>
<tr>
<td>0.3</td>
</tr>
<tr>
<td>0.7</td>
</tr>
<tr>
<td>1.2</td>
</tr>
<tr>
<td>1.5</td>
</tr>
<tr>
<td>2</td>
</tr>
</tbody>
</table>

Figure 48 shows that for these simulation parameters the static air temperatures at different ambient air temperatures do not converge and are not at the optimum with a bottom radius of 1.2 m. The static air temperatures increase with larger bottom radii and are also higher at higher ambient air temperatures, as to be expected. A solar
plant will be subject to different temperatures during the day and the performance of the power plant must be as consistent as possible. The graph shows that for this chimney height the optimum bottom radius is the largest practical radius.

![Octagon Chimney Bottom Radius versus Static Air Temperature](image)

**Figure 48**: Bottom radius versus static air temperature for the octagon chimney.

### 3.2.2.15 Chimney heat flux versus velocity

The influence of the heat flux on the velocity inside the chimney was investigated. During these simulations only the heat flux and ambient temperature were changed and all the other parameters were kept fixed. The velocities for this plant were obtained for five temperatures and for seven different heat flux values. The results of these simulations are shown in Table 25. The velocities were measured at the top of the chimney close to the outlet where the turbine will be placed.

**Table 25**: Simulation results of heat flux versus velocity.

<table>
<thead>
<tr>
<th>Heat flux (Wm(^{-2}))</th>
<th>Ambient temperature (°C)</th>
<th>9 °C</th>
<th>25 °C</th>
<th>38 °C</th>
<th>50 °C</th>
<th>62 °C</th>
</tr>
</thead>
<tbody>
<tr>
<td>50</td>
<td>1.390</td>
<td>1.394</td>
<td>1.386</td>
<td>1.392</td>
<td>1.390</td>
<td></td>
</tr>
<tr>
<td>150</td>
<td>2.086</td>
<td>2.083</td>
<td>2.038</td>
<td>2.037</td>
<td>2.043</td>
<td></td>
</tr>
<tr>
<td>250</td>
<td>2.492</td>
<td>2.488</td>
<td>2.452</td>
<td>2.452</td>
<td>2.441</td>
<td></td>
</tr>
<tr>
<td>350</td>
<td>2.818</td>
<td>2.774</td>
<td>2.758</td>
<td>2.765</td>
<td>2.763</td>
<td></td>
</tr>
</tbody>
</table>
Figure 49 show that, for these simulation parameters, the variance in heat flux produces almost the same velocity. It indicates that the velocity is directly proportional to the heat flux and not to the ambient temperature. A solar plant will be subject to different heat flux values during the year due to seasonal variations.

<table>
<thead>
<tr>
<th>Heatflux (W/m)</th>
<th>400</th>
<th>500</th>
<th>600</th>
</tr>
</thead>
<tbody>
<tr>
<td>50</td>
<td>2.929</td>
<td>3.168</td>
<td>3.356</td>
</tr>
<tr>
<td>150</td>
<td>2.954</td>
<td>3.159</td>
<td>3.397</td>
</tr>
<tr>
<td>250</td>
<td>2.906</td>
<td>3.174</td>
<td>3.368</td>
</tr>
<tr>
<td>350</td>
<td>2.901</td>
<td>3.211</td>
<td>3.367</td>
</tr>
<tr>
<td>450</td>
<td>2.898</td>
<td>3.167</td>
<td>3.356</td>
</tr>
<tr>
<td>550</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Figure 49: Heat flux versus velocity for the octagon chimney.

### 3.2.2.16 Chimney heat flux versus static air pressure

The influence of the heat flux on the static air pressure changes inside the chimney was also simulated. During these simulations only the heat flux and ambient temperature were changed and all the other parameters were kept fixed. The pressures for this plant were obtained for five temperatures and for seven different heat flux values. The results of these simulations are shown in Table 26. The air pressures were measured at the bottom (inlet aperture) and top of the chimney close to the outlet where the turbine will be placed, and the static air pressures were calculated using equation (3.1).
Figure 50 shows that for these simulation parameters, at different ambient temperatures, the variance in heat flux produces almost the same static air pressure. This indicates that the static air pressure is directly proportional to the heat flux and not to the ambient temperature. A solar plant will be subject to different heat flux values during the year due to seasonal variations.

Table 26: Simulation results of heat flux versus static air pressure.

<table>
<thead>
<tr>
<th>Heat flux (Wm(^{-2}))</th>
<th>Ambient temperature (^{0}\text{C})</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>9 (^{0}\text{C})</td>
</tr>
<tr>
<td>50</td>
<td>0.369</td>
</tr>
<tr>
<td>150</td>
<td>0.714</td>
</tr>
<tr>
<td>250</td>
<td>1.040</td>
</tr>
<tr>
<td>350</td>
<td>1.286</td>
</tr>
<tr>
<td>400</td>
<td>1.988</td>
</tr>
<tr>
<td>500</td>
<td>1.570</td>
</tr>
<tr>
<td>600</td>
<td>1.923</td>
</tr>
</tbody>
</table>
3.2.2.17 Chimney heat flux versus static air temperature

The influence of the heat flux on the static air temperature inside the chimney was also simulated. During these simulations only the heat flux and ambient temperature were changed and all the other parameters were kept fixed. The static air temperatures for this plant were obtained for five temperatures and for seven different heat flux values. The results of these simulations are shown in Table 27. The air temperatures were measured at the bottom (inlet aperture) and top of the chimney close to the outlet where the turbine will be placed, and the static air temperature was calculated using equation (3.2).

Figure 51 show that for these simulation parameters, at each ambient temperature, the variance in heat flux produces almost the same static air pressure. A solar plant will be subject to different heat flux values during the year due to seasonal variations.

Table 27: Simulation results of heat flux versus static air pressure.

<table>
<thead>
<tr>
<th>Heat flux (Wm(^{-2}))</th>
<th>9 (^{\circ})C</th>
<th>25 (^{\circ})C</th>
<th>38 (^{\circ})C</th>
<th>50 (^{\circ})C</th>
<th>62 (^{\circ})C</th>
</tr>
</thead>
<tbody>
<tr>
<td>50</td>
<td>1.862</td>
<td>1.949</td>
<td>2.061</td>
<td>2.131</td>
<td>2.214</td>
</tr>
<tr>
<td>350</td>
<td>7.918</td>
<td>7.521</td>
<td>7.960</td>
<td>8.075</td>
<td>8.373</td>
</tr>
<tr>
<td>400</td>
<td>8.584</td>
<td>8.941</td>
<td>8.728</td>
<td>8.986</td>
<td>9.203</td>
</tr>
<tr>
<td>600</td>
<td>11.554</td>
<td>10.782</td>
<td>11.768</td>
<td>11.993</td>
<td>11.652</td>
</tr>
</tbody>
</table>
3.3. Discussion of Simulation Results

3.3.1 Introduction

Two concepts were numerically simulated to evaluate the different factors that influence the performance of the solar updraft power plant. The concepts are:

- Cylindrical chimney and
- Octagon chimney with the inlet diameter larger than the output diameter.

Different parameters were evaluated for both concepts, which include:

- Static air pressure
- Velocity of the air in the chimney
- Static air temperature
- Chimney height
- Inlet aperture of the chimney

The most important difference between the two concepts is the position of the turbine in the chimney. It is at the bottom of the cylindrical chimney near the inlet aperture and at the top of the Octagon chimney near the outlet. The differences between the two concepts as used in ANSYS, are shown in Table 28.
Table 28: Comparison between the physical dimensions of both concepts.

<table>
<thead>
<tr>
<th>Physical Dimensions of the two Concepts</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Cylindrical Shape Chimney</strong></td>
</tr>
<tr>
<td><strong>Explanation</strong></td>
</tr>
<tr>
<td>Bottom diameter of the chimney</td>
</tr>
<tr>
<td>Top outlet diameter of the chimney</td>
</tr>
<tr>
<td>Height of the chimney</td>
</tr>
<tr>
<td>Inlet aperture</td>
</tr>
<tr>
<td>Collector</td>
</tr>
<tr>
<td>Height of extension</td>
</tr>
<tr>
<td>Top diameter of extension</td>
</tr>
</tbody>
</table>

3.3.2 Comparison of the simulation results between concepts

The simulations were performed using ANSYS and for both concepts the same initial boundary conditions were used, as is explained in Table 6. The comparison the most important parameters are evaluated for both concepts, and include:

- Velocity (m/s)
- Static pressure (Pa)
- Temperature (K)
- Air density (kg/m$^3$) and
- Enthalpy (J/kg)

The compared results are shown in Table 29. It shows that the velocity obtained from the octagon shaped chimney is superior to that of a cylindrical shaped chimney. The enthalpy of the octagon shaped chimney is also much larger than that of the cylindrical shaped chimney, due to the larger outer surface for heat exchange due to the shape, which has an influence on the air pressure differences. Again the octagon chimney results were superior.
Table 29: Comparison of simulation results between the two concepts.

<table>
<thead>
<tr>
<th>Comparison of Simulation Results of the two Concepts</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Cylindrical Shape Chimney</strong></td>
</tr>
<tr>
<td><strong>Explanation</strong></td>
</tr>
<tr>
<td>Velocity (m/s)</td>
</tr>
<tr>
<td>Static pressure (Pa)</td>
</tr>
<tr>
<td>Temperature (K)</td>
</tr>
<tr>
<td>Air density (kg/m$^3$)</td>
</tr>
<tr>
<td>Enthalpy (J/kg)</td>
</tr>
</tbody>
</table>

The influence of the different parameters on both concepts was also numerically evaluated, to obtain the best possible design for the chimney plant. This was achieved by keeping all the parameters fixed, except the specific parameter under investigation. The following simulations were performed on each concept:

- Chimney height (varied) versus air velocity.
- Chimney height (varied) versus static air pressure
- Chimney height (varied) versus static air temperature.
- Inlet aperture (varied) versus velocity.
- Inlet aperture (varied) versus static air pressure
- Inlet aperture (varied) versus static air temperature.

The compared results of a varied chimney height are shown in Table 30. All results shown are for an ambient temperature of 38°C. The results of a 3 m chimney show that the velocity obtained from the octagon shaped chimney is superior to that of a cylindrical shaped chimney. The static air pressure of the octagon shaped chimney is also much larger than that of the cylindrical shaped chimney. The static air temperature of the cylindrical chimney is superior to that of the octagon chimney.

The effect of a varied inlet aperture was also compared. The results of an inlet aperture of 0.27m are also shown in Table 30, because the majority of the best
results were obtained at this inlet aperture specification. The velocity and static air pressure of the octagon chimney are again superior to that of the cylindrical chimney, while the latter is again superior when the static air temperature is concerned.

Table 30: Comparison of specific results between the two concepts.

<table>
<thead>
<tr>
<th>Comparison of Simulation Results of the two Concepts</th>
<th>Cylindrical Chimney</th>
<th>Octagon Chimney</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chimney height (3 m) versus Velocity (m/s)</td>
<td>0.950 m/s</td>
<td>1.741 m/s</td>
</tr>
<tr>
<td>Chimney height (3 m) versus static air pressure</td>
<td>-0.461 Pa</td>
<td>-0.516 Pa</td>
</tr>
<tr>
<td>Chimney height (3 m) versus static air temperature</td>
<td>6.74 °C</td>
<td>1.693 °C</td>
</tr>
<tr>
<td>Inlet aperture (0.27 m) versus velocity</td>
<td>0.840 m/s</td>
<td>2.285 m/s</td>
</tr>
<tr>
<td>Inlet aperture (0.27 m) versus static air pressure</td>
<td>-1.217 Pa</td>
<td>1.067 Pa</td>
</tr>
<tr>
<td>Inlet aperture (0.27 m) versus static air temperature</td>
<td>2.584 °C</td>
<td>2.483 °C</td>
</tr>
</tbody>
</table>

The comparison of the results shows that when each individual parameter is investigated, the numerical performance of the octagon shaped chimney is in the majority of the simulations superior to the cylindrical shaped chimney. Based on the comparative numerical modelling results, the decision was taken to develop the octagon shaped chimney into a pilot plant and to compare numerical simulations with measured data of the pilot plant.
CHAPTER 4

4. NUMERICAL MODELLING AND INVESTIGATION OF THE SELECTED SOLAR CHIMNEY SYSTEM

4.1 Final Design

This section is the detailed design of the selected concept, which is the octagon shaped chimney. The maximum power that could be extracted by the turbine (at 100% efficiency) from the kinetic energy of the moving air is equal to the radiation energy from the sun, if all the radiation energy is transferred to the air. The actuator disk theory is used for this evaluation. It was first proposed by Rankine and Froude in the late 19th century. The basics of the theory are to represent the real turbine rotor with an equal area disk. Several assumptions are involved. The following assumptions were made:

- The flow of the air (fluid) is incompressible,
- The flow upstream of the air is steady and uniform,
- There is no rotational flow or turbulence produced by the air,
- The air velocity is steady and uniform,
- The flow upstream is contained by the boundary stream tube (chimney).

Using Table 31, the maximum average theoretical solar radiation power per square metre, which can be used by the turbine per day is calculated. It is assumed that the power produced per day is extracted from moving air over a period of 6 hours, between 09:00 and 15:00. The average quantity of energy amounts to:

\[ P_{el} = 3.765\text{kWh}(m^{-2}) \]  \hspace{1cm} (4.1)

The average energy in watt (J s\(^{-1}\)) per square metre is:

\[ P_{el} = 174.32\text{W}(m^{-2}) \]  \hspace{1cm} (4.2)
The total outside surface of the chimney is 7.76 m$^2$, and half the surface area is 3.88 m$^2$. The total radiation energy received by the chimney depends on the total area that is being illuminated by the sun. Two cases will be investigated:

- Case one is without reflection mirrors, resulting in only half of the chimney being illuminated at any given time, (Equation (4.3)) and.
- Case two with mirror where the total area of the chimney is illuminated (Equation (4.4)).

The maximum average daily global radiation that is received in Pretoria is achieved with a surface that is tilted 25° and facing north.

$$P_{el} = 992.22W$$  \hspace{1cm} (4.3)$$

And

$$P_{el} = 1984.45W$$  \hspace{1cm} (4.4)$$

Table 31: Hourly global radiation of Pretoria (Eberhard, 1990)

<table>
<thead>
<tr>
<th>HOUR</th>
<th>JAN</th>
<th>FEB</th>
<th>MAR</th>
<th>APR</th>
<th>MAY</th>
<th>JUN</th>
<th>JUL</th>
<th>AUG</th>
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<th>OCT</th>
<th>NOV</th>
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<td>107</td>
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<td>220</td>
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<td>0</td>
<td>0</td>
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</tr>
</tbody>
</table>
The maximum theoretical velocity that the air could reach through the chimney outlet with a diameter of \( D = 280 \) mm, to convert all the solar radiation into mechanical power, is estimated as follows:

\[
P_{el} = 992.22W = \frac{1}{2} \times m \times V_{\text{max}}^2
\]  
(4.5)

\[
P_{el} = 992.22W = \frac{1}{2} \times \rho \times Vol \times V_{\text{max}}^2
\]  
(4.6)

\[
P_{el} = 992.22W = \frac{1}{2} \times \rho \times A \times V_{\text{max}}^3
\]  
(4.7)

The density of air at \( 25^\circ C \) is \( 1.275 \) kg/m\(^3\). If the inlet area is \( 2.04 \) m\(^2\), then the inlet velocity is:

\[
P_{el} = 1984.44W = 1.2754 \times 2.04 \times V^3
\]  
(4.8)

\[
V_{in} = \sqrt[3]{\frac{1984.44}{2.60}}
\]  
(4.9)

\[
V_{\text{max-in}} = 9.14ms^{-1}
\]  
(4.10)

Since there is conservation of mass, we can do the same calculations for the chimney outlet, with an area: \( A_{\text{outlet}} = 0.062 \) m\(^2\). The output air velocity is then:

\[
V_{\text{max-out}} = 29.35ms^{-1}
\]  
(4.11)
The flow is assumed to be one-dimensional steady flow. It is also assumed that the solar radiation is absorbed by the fluid under the roof of the collector. Therefore, the friction losses as well as the heat losses are negligible.

### 4.1.1 Momentum equation

The law of the conservation of momentum is valid. This means that:

\[
P_{\text{out}} + P_E = P_{\text{in}}
\]

(4.12)

\[
\dot{m}V_{\text{out}} + \dot{m}gh_{\text{chimney}} = \dot{m}V_{\text{in}}
\]

(4.13)

### 4.1.2 Energy equation

The law of the conservation of energy is also valid. This also concludes that the kinetic energy \(E_k\), the potential energy \(P_E\) and the heat flow \(Q\) should balance out:

\[
E_{\text{in}} = E_{\text{out}}
\]

(4.14)

\[
E_{k \text{in}} + Q_{\text{in}} = E_{k \text{out}} + Q_{\text{out}} + P_E
\]

(4.15)

\[
\frac{1}{2}\dot{m}V_{\text{in}}^2 + \dot{m}C_{\text{air}}T_{\text{in}} = \frac{1}{2}\dot{m}V_{\text{out}}^2 + \dot{m}C_{\text{air}}T_{\text{out}} + \dot{m}gh_{\text{chimney}}
\]

(4.16)

When the energy balance (equation (4.16)) is investigated, the calculations show that the maximum theoretical output velocity (equation (4.15)) is only achieved with a mass flow of 23.77 kg/s when the temperature difference between the ambient temperature of 25\(^0\) C and that of the chimney is 57\(^0\) C (Table 32). Figure 52 shows the variation of the output velocities versus the temperature difference.
Table 32: Velocities versus chimney temperatures.

<table>
<thead>
<tr>
<th>Temperature</th>
<th>( V_{in} )</th>
<th>( V_{out} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>25</td>
<td>9.14</td>
<td>19.85</td>
</tr>
<tr>
<td>26</td>
<td>9.14</td>
<td>20.35</td>
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<td>20.83</td>
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<td>25.03</td>
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<td>55</td>
<td>9.14</td>
<td>29.61</td>
</tr>
</tbody>
</table>

Figure 52: Velocities versus chimney temperature.
4.1.3 The Turbine in the Chimney

It is assumed that the energy that rotates the turbine comes only from the kinetic energy from the heated air within the chimney. It is therefore assumed that the process in the chimney is adiabatic. Friction is neglected and only one-dimensional steady flow occurs. The turbine is assumed to be positioned in the top of the chimney and that the air expansion through the turbine is adiabatic and reversible. Therefore, it is isentropic. The conditions before the expansion through the turbine and after are denoted with subscript “in” and “out”, respectively.

The heat capacity of air at a constant volume $C_v$ is:

$$C_v = \frac{R}{\gamma - 1} \quad (4.17)$$

Where $R$ is the ideal gas constant of air. By reworking this equation the value of $\gamma$ can be calculated.

$$718 = \frac{287.058}{\gamma - 1} \quad (4.18)$$

$$\gamma = 1.4 \quad (4.19)$$

For turbines operating in an adiabatic environment, the equation describing the work is given in equation (4.20). The inside temperature is 330.15 K and the outside temperature is 298.15 K and atmosphere pressure at 101.13 kPa:

$$\frac{T_{out}}{T_{in}} = \left( \frac{P_{out}}{P_{in}} \right)^{\frac{\gamma - 1}{\gamma}} \quad (4.20)$$

$$\frac{298.15K}{327.15K} = \left( \frac{101.32kPa}{P_{in}} \right)^{1.4 - 1} \quad (4.21)$$
According to Koonsrisuk (2012) the theoretical power that can be extracted by the turbine can be obtained from the steady flow energy equation and from the Gibb’s equation from standard thermodynamics, which states:

\[
W_{\text{Turbine}} = \frac{\dot{m} \times \Delta P_{\text{Turbine}}}{\rho_{\text{air}}} \quad (4.24)
\]

\[
W_{\text{Turbine}} = \frac{\dot{m} \times (P_{\text{in}} - P_{\text{out}})}{\rho_{\text{air}}} \quad (4.25)
\]

\[
W_{\text{Turbine}} = \frac{23.77 \text{KgS}^{-1} \times (140.36 - 101.32) \times 10^3 \text{Pa}}{1.275 \text{Kgm}^{-3}} \quad (4.26)
\]

\[
W_{\text{Turbine}} = 727.83\text{W} \quad (4.27)
\]

The radiation power from the sun that the chimney receives is 992.22 W (equation (4.3)). The maximum energy that the turbine can extract is 727.83 W if no losses are assumed. The result is that the system is theoretically performing at 73.4% or \(0=0.734\).

Since these calculations were done for an ideal situation, it infers that for a real installation the efficiency will be much less.

### 4.1.4 Discussion

The results of the calculations show that improvements to the design can only be achieved if the following are considered:
• Pressure and velocity at the exit can only be increased if the height of the chimney is increased. Higher pressure or an increase in the pressure difference increases the likelihood that the updraft is maintained with the increase in chimney height.

• The calculations show that the velocities at the turbine exit and chimney exit can be increased if more heat is added to the system by mirrors.

4.2 Numerical modelling

4.2.1 The ANSYS Fluent simulation program

ANSYS Fluent software contains the major physical modelling capabilities needed to model flow, turbulence, and heat transfer, from airflow in a duct to airflow over a turbine.

Since fluid dynamics and thermodynamics play a critical role in the design of a solar chimney, it was used to simulate and analyze the gas flow, heat transfer and fluid dynamics of the designed system.

This engineering simulation software enabled the analysis of the solar chimney design in a virtual environment by allowing the researcher to simulate various different options in a reasonable time frame without any physical changes to a prototype.

4.2.2 Constructing the Solar Chimney model in ANSYS

The design of the solar chimney is transferred into the ANSYS software through a module called the “Geometry – Design Modeller”. The purpose is to have the system as shown in Figure 53, in the software to model the air flow, heat flow and thermodynamic properties of the system in three dimensions (3D). In order to achieve this, each part of the designed solar chimney was redrawn in the software and combined to have the complete 3D model. The model parameters and dimensions are given in Table 33.
Figure 54 and Figure 55 show the views of the completed solar plant model as it has been transferred into ANSYS.

Table 33: Explanation of symbols and dimensions used in ANSYS:

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Explanation</th>
<th>Physical dimensions</th>
</tr>
</thead>
<tbody>
<tr>
<td>D&lt;sub&gt;c&lt;/sub&gt;</td>
<td>Bottom diameter of the chimney</td>
<td>2.4 m</td>
</tr>
<tr>
<td>d&lt;sub&gt;c&lt;/sub&gt;</td>
<td>Top outlet diameter of the chimney</td>
<td>0.28 m</td>
</tr>
<tr>
<td>L&lt;sub&gt;c&lt;/sub&gt;</td>
<td>Height of the chimney</td>
<td>2.0 m</td>
</tr>
<tr>
<td>I</td>
<td>Inlet aperture</td>
<td>0.27 m</td>
</tr>
<tr>
<td>D&lt;sub&gt;p&lt;/sub&gt;</td>
<td>Steel plate diameter</td>
<td>4.00 m</td>
</tr>
<tr>
<td>L&lt;sub&gt;e&lt;/sub&gt;</td>
<td>Height of extension</td>
<td>0.57 m</td>
</tr>
<tr>
<td>D&lt;sub&gt;e&lt;/sub&gt;</td>
<td>Top diameter of extension</td>
<td>0.87 m</td>
</tr>
</tbody>
</table>

Figure 53: The solar chimney design that was modelled in the ANSYS Fluent Simulation Program.

The complete model was constructed from individual sections or parts. In the next section these individual sections will be discussed in more detail.
Figure 54: Slanted isometric view of the solar power plant in ANSYS.

Figure 55: Side view of the solar power plant in ANSYS.
4.2.2.1 Base Plate

The base plate is placed under the chimney to give it a firm fixed base to stand on. The pilot plant was constructed on the roof of a six (6) level building at the campus, where it was stable against the wind and prevented from toppling over.

It absorbs a little heat and radiation from the sun, although it was not meant to act as a solar collector. However, the base plate did collect a tiny amount of energy to drive the heat flow through the chimney. The material used to construct the base plate was 3 mm mild steel sheets with a mat black finish. The dimensions of the base plate are 5 m in diameter (Figure 56). The thickness of the plate is not important as it was not meant to act as a solar collector. The rest of the solar chimney was constructed on the base plate and also hoisted to the roof in sections (Figure 57 and Figure 58).

Figure 56: Solar power plant base plate with an area of 25 m² in ANSYS.
Figure 57: Sections of the solar chimney plant hoisted to the roof of the building.

Figure 58: Base plate being hoisted towards the roof of the building.
4.2.2.2 Inlet aperture

The inlet aperture (Figure 59) plays an important role in sustaining the flow of air through the chimney. The inlet aperture regulates the air flow into the solar plant, and it is assumed, ideally at a constant flow rate. The chimney was constructed 270 mm above the base plate on eight small steel legs, which were welded onto the base plate and the bottom section of the solar chimney. The steel legs were 20 mm square steel tubing and their influence on the airflow and the inlet aperture surface area is assumed to be legible.

The result of this is that the surface area of the inlet aperture around the base of the solar chimney is 2.04 m². The ratio between the top outlet of the chimney and the inlet aperture is 1:8. The ratio between the area of the base plate and the area of the inlet aperture is 12:1.

![Figure 59: Solar power plant inlet aperture in ANSYS.](image)

4.2.2.3 Chimney

The chimney (Figure 60) is in the shape of an eight-sided cone. The rationale for this design is discussed in chapter 3 under section 3.3 “Concept selection for the numerical simulations”. The chimney is manufactured from a 20 mm square steel
tubing structure covered by 2 mm thick steel sheeting. The chimney is painted black to provide efficient solar radiation and heat absorption of the sun during the day. The height of the chimney in this design is 2 m, without the extension.

Each section of the octagon that comprises the chimney is 0.86 m at the bottom and 0.11 m at the top. The slanted length of each section is 2.96 m. This translates into a total outside surface area of 7.76 m² of the chimney. The efficiency of the chimney (conversion of heat into kinetic energy) is practically independent of ΔT in the base plate. It depends solely on the temperature difference between the ambient temperature and that of the air column in the chimney; as in the case with any Rankine cycle. The larger the temperature difference, the higher the efficiency of the chimney. Another aspect is also very important when solar chimneys are concerned; namely, the height of the chimney. Higher chimneys are more efficient.

Figure 60: Solar power plant chimney in ANSYS.

4.2.2.4 Turbine
The turbine (Figure 22) is mounted in the centre close to the outlet of the chimney. The rising hot incoming air through the inlet aperture turns the turbine. Ideally, the
turbine will turn constantly during the day, depending on the daily weather conditions. Since the solar chimney pilot plant is very small, a very small size turbine was chosen. The reason for this decision was that literature suggests that the overall efficiency of solar updraft plants varies from 1% to 2% (Chikere et. al, 2011). Since the maximum solar radiation energy on the chimney is only 992.22 W, one percent is only 10 W. However this efficiency is with a solar collector and in this case it is absent.

4.2.2.5 Extension
The chimney outlet extension (Figure 61) covers the turbine and is in the form of a cone. It is constructed of 1 mm mild steel sheeting with a mat black finish. The purpose of the extension is to reduce outlet turbulence of the air. The ratio between the chimney outlet and the bottom inlet of the extension is 1:1. The ratio between the bottom inlet and the top outlet of the extension is 1:2. The top outlet diameter of the extension is thus 870 mm and the height of the extension is 2.11 times the height of the inlet aperture, and thus totals 570 mm.

Figure 61: Solar power plant outlet extension in ANSYS.
4.3 Equations used in the simulations

4.3.1 Pressure Equation

The pressure difference ($\Delta P$) between the inside of the chimney and the outside is the driving force for the so-called “stack effect”, and it can be calculated with the equation presented below. The equation applies only to chimneys where air is both inside and outside the chimneys. The symbol $h$ is the height of the chimney and is the distance from the opening at the neutral pressure level (NPL) of the chimney to the topmost opening. The difference in pressure is given by the following relationship, and the symbols are explained in Table 34 below:

$$\Delta P = C_{air} P_0 h \left( \frac{1}{T_0} - \frac{1}{T_i} \right)$$  

(4.28)

Table 34: Explanation of the symbols used in equation (4.28).

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Explanation</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta P$</td>
<td>Available pressure difference, in Pa</td>
</tr>
<tr>
<td>$C_{air}$</td>
<td>Heat Capacity of air = 0.0342</td>
</tr>
<tr>
<td>$P_0$</td>
<td>Atmospheric pressure, in Pa</td>
</tr>
<tr>
<td>$h$</td>
<td>Height in m</td>
</tr>
<tr>
<td>$T_o$</td>
<td>Absolute outside temperature, in K</td>
</tr>
<tr>
<td>$T_i$</td>
<td>Absolute inside temperature, in K</td>
</tr>
</tbody>
</table>

The draft flow rate induced by the stack effect can be calculated with equation (4.29), presented below. The equation applies only to chimneys where air is both inside and outside the chimney. The symbols are explained in Table 35 below in SI units.

$$Q = C_D A_{flow} \sqrt{2gh \frac{T_i - T_0}{T_i}}$$  

(4.29)
Table 35: Explanation of symbols for equation (4.29).

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Explanation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Q</td>
<td>Flow rate in m$^3$/s</td>
</tr>
<tr>
<td>$C_D$</td>
<td>Discharge coefficient (usually taken to be from 0.65 to 0.70)</td>
</tr>
<tr>
<td>$A_{flow}$</td>
<td>Flow area in m$^2$</td>
</tr>
<tr>
<td>g</td>
<td>Gravity acceleration = 9.81 m/s$^2$</td>
</tr>
<tr>
<td>h</td>
<td>Height in m</td>
</tr>
<tr>
<td>$T_o$</td>
<td>Absolute outside temperature, in K</td>
</tr>
<tr>
<td>$T_i$</td>
<td>Absolute inside temperature, in K</td>
</tr>
</tbody>
</table>

4.3.2 The Energy Equation

The energy equation that is used in the ANSYS FLUENT software is the Compressible Euler Equation (equation (4.30)). The equation above thus represents conservation of mass, momentum, energy. Mass density, flow velocity and pressure are the so-called physical variables, while mass density, momentum density and total energy density are the so-called conserved variables. The symbols are explained in Table 36.

$$\frac{\partial}{\partial t}(\rho E) + \nabla \cdot (\rho \vec{v} (\rho E + p)) = \nabla \cdot \left( k_{eff} \nabla T - \sum_j h_j \vec{j}_j + (i_{eff} \vec{v}) \right)$$ (4.30)

The first three terms on the right hand side represent energy transfer due to conduction, species diffusion and viscous dissipation. The terms on the left hand side represent pressure work, kinetic energy and radiations source terms.

Table 36: Symbol explanation of the Euler Energy Equation

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Explanation</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\frac{\partial}{\partial t}$</td>
<td>Variation in time (t)</td>
</tr>
<tr>
<td>$\Delta$</td>
<td>Density of the medium</td>
</tr>
<tr>
<td>E</td>
<td>Energy</td>
</tr>
<tr>
<td>$\nabla$</td>
<td>“Del Operator”</td>
</tr>
</tbody>
</table>
The energy equation that is used in the ANSYS FLUENT software for solid regions and energy transport is given in Equation (4.31).

The first term on the left hand side deals with the enthalpy, while the second term deals with the convective energy due to rotation and translation in solids. The velocity field $\vec{v}$ is computed from the motion specified for the solid zone.

The terms on the right hand side of Equation (4.31) represent the heat flux due to isotropic conduction and heat sources within the solid. Table 37 explains the symbols.

$$\frac{\partial}{\partial t} (\rho h) + \nabla \cdot (\vec{v} \rho h) = \nabla \cdot (k \nabla T) + S_h$$  \hspace{1cm} (4.31)

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Explanation</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\frac{\partial}{\partial t}$</td>
<td>Variation in time (t)</td>
</tr>
<tr>
<td>$\Delta$</td>
<td>Density of the medium</td>
</tr>
<tr>
<td>$h$</td>
<td>Enthalpy</td>
</tr>
<tr>
<td>$\nabla$</td>
<td>“Del Operator”</td>
</tr>
<tr>
<td>$\vec{v}$</td>
<td>Velocity vector</td>
</tr>
<tr>
<td>$k$</td>
<td>Isotropic Conductivity</td>
</tr>
<tr>
<td>$T$</td>
<td>Temperature</td>
</tr>
<tr>
<td>$S_h$</td>
<td>Other heat sources</td>
</tr>
</tbody>
</table>

Table 37: Symbol explanation of the Energy Equation in Solid Regions
The next equations that are an integral section of the numerical modelling or simulation of the Solar Chimney are the Momentum Conservation Equations. These equations model the conservation of momentum in an inertial, non-accelerating reference frame (Equation (4.32)). Table 38 explains the symbols in the equation.

\[
\frac{\partial}{\partial t} (\rho \vec{v}) + \nabla \cdot (\rho \vec{v} \vec{v}) = -\nabla p + \nabla \cdot (\vec{t}) + \rho \vec{g} + \vec{F} \tag{4.32}
\]

Table 38: Symbol explanation of the Momentum Conservation Equation

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Explanation</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\frac{\partial}{\partial t})</td>
<td>Variation in time (t)</td>
</tr>
<tr>
<td>(\Delta)</td>
<td>Density of the medium</td>
</tr>
<tr>
<td>(\vec{v})</td>
<td>Velocity Vector</td>
</tr>
<tr>
<td>(\nabla)</td>
<td>“Del Operator”</td>
</tr>
<tr>
<td>(p)</td>
<td>Pressure</td>
</tr>
<tr>
<td>(\vec{t})</td>
<td>Stress Tensor</td>
</tr>
<tr>
<td>(g)</td>
<td>Gravity Acceleration</td>
</tr>
<tr>
<td>(\vec{F})</td>
<td>Other Sources</td>
</tr>
</tbody>
</table>

The flow of air in the chimney is turbulent. Reynolds-averaged Navier–Stokes equations (or RANS equations) are time-averaged equations of motion for fluid flow. The idea behind the equations is Reynolds decomposition, whereby an instantaneous quantity is decomposed into its time-averaged and fluctuating quantities (Randall, 2014).

It is neither feasible nor desirable to consider in detail all of the small-scale fluctuations that occur in the chimney. For this reason, we introduce averaging or smoothing operators, and attempt to describe only the average state of the air flow in the chimney, following the approach of “Reynolds Averaging.” However, this leads, to additional terms in the governing equations for the averaged quantities. The additional terms represent the effects of “eddy fluxes” that arise from the motion that have been removed by the averaging procedure (Randall, 2014).
Depending on the context in which the Reynolds averaging procedure is being used, and the nature of the averaging operator adopted, the eddy fluxes can arise from turbulence, from Chimney convection, from gravity influences, from inconsistent temperature effects or from influences around the inlet aperture.

The RANS equations are primarily used to describe turbulent flows. These equations can be used with approximations based on knowledge of the properties of flow turbulence in the chimney to give approximate time-averaged solutions to the Navier–Stokes equations.

The ANSYS simulation software solves for the instantaneous Navier-Stokes equations by calculating the fluctuating components by decomposing it into the mean ensemble-averaged or time averaged components. This is done for the different velocity and pressure components (Equation (4.33) and Equation (4.34)).

\[ v_i = \bar{v}_i + v'_i \]  \hspace{1cm} (4.33)

Where the first term on the right hand side is the average velocity and the second term is the variation of the average. Likewise for the pressure:

\[ p_i = \bar{p}_i + p'_i \]  \hspace{1cm} (4.34)

These equations for the flow variables are then substituted into the transport equations for the standard \( k-\gamma \) model.

Two turbulence models in the ANSYS software allow for the determination of a turbulent length and time by solving two separate transport equations. The standard \( k-\gamma \) model used in ANSYS was proposed by Launder and Spalding in 1974, and is used as the major approach in solving turbulent flow characteristics. The turbulence kinetic energy \( k \) and the rate of dissipation \( \gamma \) are obtained from the following equations:
\[
\frac{\partial}{\partial t}(\rho k) + \frac{\partial}{\partial x_i} (\rho k v_i) = \frac{\partial}{\partial x_j} \left[ (\mu + \frac{\mu_t}{\sigma_k}) \frac{\partial k}{\partial x_j} \right] + G_k + G_b - \rho \varepsilon - Y_M + S_k \quad (4.35)
\]

\[
\frac{\partial}{\partial t}(\rho \varepsilon) + \frac{\partial}{\partial x_i} (\rho \varepsilon v_i) = \frac{\partial}{\partial x_j} \left[ (\mu + \frac{\mu_t}{\sigma_\varepsilon}) \frac{\partial \varepsilon}{\partial x_j} \right] + \frac{\varepsilon}{k} (G_k + C_{2\varepsilon} G_b) - C_{2\varepsilon} \rho \frac{\varepsilon^2}{k} + S_\varepsilon \quad (4.36)
\]

In these equations $G_k$ represents the generation of turbulent kinetic energy due to the mean velocity gradients. $G_b$ is the generation of turbulent kinetic energy due to buoyancy. $Y_M$ represents the contribution of the fluctuating dilation in compressible turbulence of time. The following are the model constants with the default values determined through experimentation: $C_{1\gamma}=1.44$, $C_{2\gamma}=1.92$, $C_{3\gamma}=0.09$, $\Phi_k=1.0$ and $\Phi_\gamma=1.3$. $S_k$ and $S_\gamma$ are user defined terms. The term $\varepsilon$ is called the turbulent or Eddy viscosity and is defined as:

\[
\mu_t = \rho C_{\mu} \frac{k^2}{\varepsilon} \quad (4.37)
\]

### 4.4 Weather conditions

Weather conditions are a major influence on the daily efficiency of the solar power plant, since the amount of energy produced per day by the plant is dependent on the heat radiation from the sun. Figure 62 is a graphical example of weather results for a 48 hour cycle. For this reason, two different weather condition cases were simulated in the ANSYS Fluent simulation program; namely, a winter’s day with a low ambient temperature, and a high temperature summer’s day in Pretoria, respectively.
4.5 Results from the simulations

The ANSYS Fluent program (as is discussed in the previous section) was used to model and simulate two different weather and temperature condition cases for Pretoria, South Africa. The simulations were for the chimney design as portrayed in section 4.1 of this chapter. This is necessary due to the fact that a full scale Solar Updraft Plant will operate through the year and different conditions will apply. This section presents results obtained from each case.

4.5.1 First Case: Winter’s day in Pretoria

The first case presented is a typical winter’s day in Pretoria. The following parameters were used in ANSYS to simulate the following condition:

- Ambient temperature: $17^0 \text{C}$
- Steel Plate Temperature: $30^0 \text{C}$
- Pressure (Atmospheric): 101.325 kPa
- Wind speed: 0 m/s
- Materials: Steel and atmospheric air
- Air Density at $17^0 \text{C}$: $\Delta = 1.216534 \text{ kg/m}^3$
- Gravitational Acceleration
  - X Axis $0 \text{ m/s}^2$
  - Y Axis $-9.81 \text{ m/s}^2$
  - Z Axis $0 \text{ m/s}^2$
The results for this simulation in ANSYS are given in Table 39 below. The simulations were performed by assigning simulation intervals that commenced from the inlet aperture, through the length (height) of the chimney till the top of the extension. The values summarised in Table 39 are the simulation results on the inside of the solar power plant at the centre vertical axis of the chimney.

The intervals depicted in the first column of Table 39, focus on three sections within the chimney. Section 1 is from -0.2 m to 0.00 m, and shows the values for the inlet aperture of the power plant. The intervals 0.0 m to 2.0 m classify the chimney and intervals 2.0 m to 3.2 m are the extension. The following sections will show the results for all the relevant physical entities which are important for the evaluation of the solar plant. Static air pressure as indicated in the table is the pressure difference obtained against atmospheric pressure. The area equation is from table 3 and air density from equation (2.1).

<table>
<thead>
<tr>
<th>Interval (m)</th>
<th>Area (m²)</th>
<th>Air Density (kg/m³)</th>
<th>Velocity (m/s)</th>
<th>Static Air Pressure (Pascal)</th>
<th>Static Air Temp (K)</th>
<th>Enthalpy (J/kg)</th>
<th>Kinetic Energy (J/kg)</th>
<th>Total Energy (J/kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>-0.20</td>
<td>1.16</td>
<td>1.19</td>
<td>1.06</td>
<td>-0.16</td>
<td>297.46</td>
<td>10694.23</td>
<td>0.81</td>
<td>10695.04</td>
</tr>
<tr>
<td>0.00</td>
<td>1.16</td>
<td>1.20</td>
<td>0.99</td>
<td>-0.15</td>
<td>293.31</td>
<td>4368.15</td>
<td>0.67</td>
<td>4368.82</td>
</tr>
<tr>
<td>0.30</td>
<td>0.94</td>
<td>1.21</td>
<td>0.60</td>
<td>-0.15</td>
<td>292.25</td>
<td>1447.82</td>
<td>0.13</td>
<td>1447.94</td>
</tr>
<tr>
<td>0.60</td>
<td>0.74</td>
<td>1.21</td>
<td>0.68</td>
<td>-0.14</td>
<td>292.29</td>
<td>1305.53</td>
<td>0.14</td>
<td>1305.67</td>
</tr>
<tr>
<td>0.90</td>
<td>0.56</td>
<td>1.21</td>
<td>0.81</td>
<td>-0.11</td>
<td>292.45</td>
<td>1262.57</td>
<td>0.18</td>
<td>1262.75</td>
</tr>
<tr>
<td>1.20</td>
<td>0.41</td>
<td>1.21</td>
<td>0.91</td>
<td>-0.08</td>
<td>292.70</td>
<td>1156.30</td>
<td>0.19</td>
<td>1156.49</td>
</tr>
<tr>
<td>1.50</td>
<td>0.28</td>
<td>1.20</td>
<td>1.07</td>
<td>-0.03</td>
<td>293.13</td>
<td>1080.04</td>
<td>0.21</td>
<td>1080.25</td>
</tr>
<tr>
<td>1.80</td>
<td>0.18</td>
<td>1.20</td>
<td>1.49</td>
<td>0.00</td>
<td>293.62</td>
<td>1121.61</td>
<td>0.36</td>
<td>1121.96</td>
</tr>
<tr>
<td>2.00</td>
<td>0.12</td>
<td>1.20</td>
<td>2.10</td>
<td>-0.04</td>
<td>294.04</td>
<td>1182.77</td>
<td>0.67</td>
<td>1183.43</td>
</tr>
<tr>
<td>2.30</td>
<td>0.17</td>
<td>1.22</td>
<td>0.01</td>
<td>0.01</td>
<td>290.15</td>
<td>0.01</td>
<td>0.00</td>
<td>0.01</td>
</tr>
<tr>
<td>2.60</td>
<td>0.18</td>
<td>1.22</td>
<td>0.10</td>
<td>0.01</td>
<td>290.16</td>
<td>0.19</td>
<td>0.00</td>
<td>0.19</td>
</tr>
<tr>
<td>2.90</td>
<td>0.21</td>
<td>1.22</td>
<td>0.22</td>
<td>0.04</td>
<td>290.17</td>
<td>0.88</td>
<td>0.00</td>
<td>0.88</td>
</tr>
<tr>
<td>3.20</td>
<td>0.24</td>
<td>1.22</td>
<td>0.41</td>
<td>-0.01</td>
<td>290.17</td>
<td>2.70</td>
<td>0.01</td>
<td>2.71</td>
</tr>
</tbody>
</table>

### 4.5.1.1 Static Air Pressure results

Static air pressure is investigated to evaluate the airflow path inside the chimney of the solar power plant. Differences in the static air pressure at height through the chimney create a positive static air pressure and create the updraft; resulting in the
movement of air upwards through the chimney of solar power plant from the inlet aperture to turn the turbine mounted at the outlet of the chimney. The simulation results obtained with the ANSYS software of the variations of the static air pressure are shown in Figure 63 and Figure 64.

Figure 63: 3D Colour contour graph of static air pressure within the solar chimney as simulated in ANSYS.

Figure 64: 3D contour graph of static air pressure within the solar chimney as simulated in ANSYS (front view full section).
The 3D image in Figure 63 shows very clearly that the static air pressure gradient is the largest negative at the bottom of the chimney and decreases steadily throughout the chimney towards the top. The pressure at the bottom in the chimney flue is lower (the lowest) than the ambient pressure, which creates the draft. The pressure gradient decreases through the output and extension again as the energy source is removed.

Figure 64 (full front view section) of the solar plant shows the same result. The image also shows that the base plate, although it is very small and it not functioning as a solar collector, supports an increase in the gradient of the static air pressure in the lower third of the flue towards the sides (less in the centre) of the solar power plant.

Figure 65 shows the association between static air pressures at defined height intervals within the chimney. The figure indicates that the flue pressure increases with height in the chimney and approaches the ambient value in the extension, and reduces and oscillates close to ambient pressure after it passed through the venture tube.

![Winter's Day Static Air Pressure](image)

Figure 65: Graphic presentation of static air pressure in the flue at different height intervals as simulated in ANSYS.
Figures 63, 64 and 65 indicate that the simulation results of static air pressure inside the flue supports the mechanism that controls the flow of air which is called the "natural draught", "natural ventilation", "chimney effect", or "stack effect".

4.5.1.2 Velocity in Y direction (upwards)

The vertical velocity of the air flow inside the flue is created by the rate at which the air flows into the chimney of the pilot plant through the inlet aperture at the bottom. The velocity inside the solar power plant is determined by the rate of change of the vertical movement of the air at a specific position inside the chimney. The simulated velocity differences are presented in the 3D image (Figure 66).

![Figure 66: 3D contour graph of velocity inside the chimney as simulated in ANSYS.](image)

Figure 66 and Figure 67 show that the velocity is the lowest at the bottom of the chimney. The figures show that the air accelerates against gravity and the velocity increases from the inlet vertical in the flue to turn the turbine at the top of the chimney, where the air velocity is the largest. In the front view full section of the solar power plant (Figure 67) it is also clear that the velocity increases through the pilot plant upwards to turn the turbine.

Figure 68 shows the association between vertical air velocities at defined height intervals within the chimney. The figure indicates that the velocities increases with
height in the chimney and approaches a maximum value at the outlet into the extension and decreases very rapidly.

Figure 67: 3D contour graph of the air velocity within the solar chimney as simulated in ANSYS (front view full section).

Figures 66, 67 and 68 indicate that the simulation results of air velocities inside the flue supports the mechanism that controls the air flow which is called the "natural draught", "natural ventilation", "chimney effect", or "stack effect".

Figure 68: Graphic presentation of vertical air velocity in the flue at different height intervals as simulated in ANSYS.
4.5.1.3 Static Air Temperature (Kelvin)

The static air temperature of the air inside the chimney is due to the heat absorbed from the solar radiation of the sun by the steel plates of which the chimney is manufactured. As a result hot air is flowing through the solar power plant. The simulated static air temperatures are presented in Figure 69. This 3D contour graph shows that the static air temperature inside the solar power plant is higher than ambient temperature.

Figure 69: 3D contour graph of static air temperature contours inside the chimney as simulated in ANSYS.

Figure 70 shows full front view section of the solar power plant. It shows that the temperature is the largest at the bottom of the chimney. The temperature decreases slightly upwards through the chimney of the solar power plant, due to the movement of heated air inside the solar power plant. Again the influence of the base plate on the temperature can also be seen at the bottom of the chimney. This is due to the fact that the base plate also absorbs heat from the solar radiation and stimulates the flow of hot air through the solar power plant.
Figure 70: 3D graph of static air temperature contours simulated in ANSYS (front view full section).

Figure 71: Graphic presentation of static air temperature at height intervals simulated in ANSYS.

Figure 71 shows that the static air temperature first decreases sharply upwards towards the top of the chimney extension and then increases slightly towards the
outlet. After the outlet it decreases sharply to be equal to the ambient temperature. Figures 69, 70 and 71 indicate that the temperature changes according to the hot air flow through the inside of the solar power plant.

4.5.1.4 Air Density

The heating of air inside and at the bottom of a chimney causes the lowering of the air density at the bottom. The lowering of the air density at the inside and at the bottom of the chimney causes this air to rise towards the top and is one of the causes for the chimney updraft. Air density variations in the power plant are associated with variations of temperature throughout the chimney.

The simulations in ANSYS (Figure 72 and Figure 73) show the density variations through the chimney. Figure 73 shows that the largest densities are obtained at the sides of the chimney. The lowest densities are obtained in the middle of the chimney due to the fact that the temperature transfer to the air increases the temperature and thus lowers the density.

Figure 72: 3D contour graph of air density as simulated in ANSYS.
Figure 73 shows the density variations in the 3D image of the full front view of the solar plant. The image shows that the density of the air is the lowest in the middle of the flue and that the density increases towards the sides of the chimney. It also shows that the air density outside the solar power plant is significantly higher than inside.

The behaviour of the density distribution through the chimney should be viewed in conjunction with Figure 72, which depicts the temperature distribution through the chimney. The lowest air densities (Figure 74) are directly associated with the highest temperatures in the chimney (Figure 71).

The air densities also increase slightly through the solar chimney upwards as the temperature decreases. The same association can also be made between the air density and the pressure inside the chimney (Figure 65), although not as profound.

Figure 74 presents the air densities in the flue at the defined height intervals inside the chimney. The figure shows that air density initially increases slightly upwards through the chimney within the first 0.5 m. The air density then slight decreases as
expected towards the outlet at 2 m, due to the fact that the air temperature increases. After that it sharply increases to reach the ambient air density.

![Winter's Day Air Density](image)

Figure 74: Graphic presentation of air density at height intervals simulated in ANSYS.

### 4.5.1.5 Total Energy

The Total energy is the combination of kinetic energy and enthalpy. The kinetic energy in this case is dependent on the mass and the velocity of the moving air inside the chimney. The enthalpy is the heat energy contained in the heated air, which causes the movement of the air from one height interval to the next. The combined energy turns the turbine to generate electrical power.

Figure 75 shows a 3D graph of the enthalpy numerical modelling results as obtained from the ANSYS software. It depicts the larger enthalpy inside the solar power plant due to the temperature of heated air.

The behaviour of the enthalpy distribution through the chimney should be viewed in conjunction with Figure 71, which depicts the temperature distribution through the chimney. The high enthalpies (Figure 75) in the middle of the chimney are directly associated with the highest temperatures in the chimney (Figure 71).
The enthalpy also decreases slightly through the solar chimney upwards as the temperature decreases. However the total energy increases as the kinetic energy increases upwards.

![Figure 75: Graphic 3D presentation of enthalpy in the chimney as simulated in ANSYS.](image)

The full front view section (Figure 76) shows that the enthalpy decreases through the solar power plant upwards according to the movement of heated air inside the solar power plant and correlates with the temperature distribution inside the chimney.

![Figure 76: Graphic presentation of the enthalpy distribution inside the chimney as simulated in ANSYS (front view full section).](image)
Figure 77 shows the enthalpy at defined height intervals inside the chimney. The graph clearly shows that the enthalpy decreases towards the top of the extension. There is a sharp decrease in the enthalpy again at 2 m when the heated air flows through the outlet into the ambient atmosphere. The enthalpy increases in the chimney as the temperature of the air increases due to the solar radiation. The enthalpy then slowly decreases upwards to about 2 m. At 2 m (outlet) the energy is adiabatically extracted from the air by the turbine. Lastly the enthalpy decreases again as the air is circulated back into the atmosphere.

The graph in Figure 78 shows a steady increase of the kinetic energy of the air at in the inlet of 0.3 m to 1.5 m of the chimney. The kinetic energy then increases sharply towards the outlet at 2 m, where the flow area is the smallest. It then sharply decreases as it enters into the atmosphere from the outlet of the chimney. This is due to the acceleration of the Venturi effect from the outlet into the outlet funnel.

The Venturi principle state that a fluid's velocity must increase as it passes through a constriction in accord with the principle of continuity, while its static pressure must decrease in accord with the principle of conservation of mechanical energy. Thus any gain in kinetic energy a fluid may accrue due to its increased velocity through a constriction is balanced by a drop in pressure. As the air moves upward through the

![Winter's Day Enthalpy](image-url)
chimney, the pressure increases due to the smaller diameter of the outlet. The moment it passes through the outlet and the pressure decreases, the air accelerates.

![Winter's Day Kinetic Energy](image)

**Figure 78**: Graphic presentation of kinetic energy in the chimney at different intervals as simulated in ANSYS.

The graph in Figure 79 shows the total energy (enthalpy and kinetic energy) at the different intervals inside the solar power plant.

![Winter's Day Total Energy](image)

**Figure 79**: Graphic presentation of the total energy in the chimney at different height intervals.
The shape of the total energy graph is practically identical to that of the enthalpy, showing that the contribution of the kinetic energy to the total energy inside the solar power plant is insignificant.

4.6.1 Second Case: Summer’s Day in Pretoria

The second simulation case presented here is for a summer’s day in Pretoria. The following parameters were used in ANSYS to simulate the following condition:

- Ambient temperature: 38°C
- Steel Plate Temperature: 60°C
- Pressure (Atmospheric): 101.325 kPa
- Wind speed: 0 m/s
- Materials: Steel and atmospheric air
- Air Density at 38°C: \( \Delta = 1.134428 \text{ kg/m}^3 \)
- Gravitational Acceleration
  - X Axis 0 m/s\(^2\)
  - Y Axis - 9.81 m/s\(^2\)
  - Z Axis 0 m/s\(^2\)

The results for this simulation in ANSYS are given in Table 40 below. The simulations were performed by assigning simulation intervals that commenced from the inlet aperture, through the length (height) of the chimney till the top of the extension. The values summarised in Table 40 are the simulation results on the inside of the solar power plant at the centre vertical axis of the chimney.

The intervals depicted in the first column of Table 40, focus on three sections within the chimney. Section 1 is from -0.2 m to 0.00 m, and shows the values for the inlet aperture of the power plant. The intervals 0.0 m to 2.0 m classify the chimney and intervals 2.0 m to 3.2 m are the extension. The following sections will show the results for all the relevant physical entities which are important for the evaluation of the solar plant. Static air pressure as indicated in the table is the pressure difference obtained against atmospheric pressure. The area equation is from table 3 and air density from equation (2.1).
Table 40: Simulation results for a summer's day in Pretoria.

<table>
<thead>
<tr>
<th>Interval</th>
<th>Area</th>
<th>Air Density</th>
<th>Velocity</th>
<th>Static Air Pressure</th>
<th>Static Air Temp</th>
<th>Enthalpy</th>
<th>Kinetic Energy</th>
<th>Total Energy</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(m²)</td>
<td>(kg/m³)</td>
<td>(m/s)</td>
<td>(Pascal)</td>
<td>(K)</td>
<td>(J/kg)</td>
<td>(J/kg)</td>
<td>(J/kg)</td>
</tr>
<tr>
<td>-0.20</td>
<td>1.16</td>
<td>1.09</td>
<td>1.29</td>
<td>-0.22</td>
<td>323.36</td>
<td>20086.46</td>
<td>1.369</td>
<td>20087.83</td>
</tr>
<tr>
<td>0.00</td>
<td>1.16</td>
<td>1.12</td>
<td>1.30</td>
<td>-0.20</td>
<td>316.57</td>
<td>9181.96</td>
<td>1.432</td>
<td>9183.39</td>
</tr>
<tr>
<td>0.30</td>
<td>0.94</td>
<td>1.12</td>
<td>0.70</td>
<td>-0.19</td>
<td>314.69</td>
<td>2636.90</td>
<td>0.183</td>
<td>2637.08</td>
</tr>
<tr>
<td>0.60</td>
<td>0.74</td>
<td>1.12</td>
<td>0.80</td>
<td>-0.18</td>
<td>314.79</td>
<td>2417.34</td>
<td>0.210</td>
<td>2417.55</td>
</tr>
<tr>
<td>0.90</td>
<td>0.56</td>
<td>1.12</td>
<td>0.98</td>
<td>-0.15</td>
<td>315.12</td>
<td>2455.47</td>
<td>0.296</td>
<td>2455.77</td>
</tr>
<tr>
<td>1.20</td>
<td>0.41</td>
<td>1.12</td>
<td>1.14</td>
<td>-0.10</td>
<td>315.55</td>
<td>2304.32</td>
<td>0.337</td>
<td>2304.65</td>
</tr>
<tr>
<td>1.50</td>
<td>0.28</td>
<td>1.12</td>
<td>1.37</td>
<td>-0.03</td>
<td>316.17</td>
<td>2154.25</td>
<td>0.398</td>
<td>2154.65</td>
</tr>
<tr>
<td>1.80</td>
<td>0.18</td>
<td>1.11</td>
<td>1.91</td>
<td>-0.01</td>
<td>316.84</td>
<td>2186.26</td>
<td>0.695</td>
<td>2186.95</td>
</tr>
<tr>
<td>2.00</td>
<td>0.12</td>
<td>1.11</td>
<td>2.67</td>
<td>-0.08</td>
<td>317.52</td>
<td>2281.95</td>
<td>1.274</td>
<td>2283.22</td>
</tr>
<tr>
<td>2.30</td>
<td>0.17</td>
<td>1.13</td>
<td>0.06</td>
<td>0.02</td>
<td>311.18</td>
<td>0.38</td>
<td>0.000</td>
<td>0.38</td>
</tr>
<tr>
<td>2.60</td>
<td>0.18</td>
<td>1.13</td>
<td>0.24</td>
<td>0.02</td>
<td>311.25</td>
<td>4.77</td>
<td>0.001</td>
<td>4.77</td>
</tr>
<tr>
<td>2.90</td>
<td>0.21</td>
<td>1.13</td>
<td>0.45</td>
<td>0.01</td>
<td>311.31</td>
<td>16.81</td>
<td>0.011</td>
<td>16.82</td>
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<tr>
<td>3.20</td>
<td>0.24</td>
<td>1.13</td>
<td>0.75</td>
<td>0.01</td>
<td>311.34</td>
<td>39.30</td>
<td>0.057</td>
<td>39.35</td>
</tr>
</tbody>
</table>

4.6.1.1 Static Air Pressure results

Static air pressure is investigated to evaluate the airflow path inside the chimney of the solar power plant. Differences in the static air pressure at height through the chimney create a positive static pressure and create the updraft; resulting in the movement of air upwards through the chimney of solar power plant from the inlet aperture to turn the turbine mounted at the outlet of the chimney. The simulation results obtained with the ANSYS software of the variations of the static air pressure are shown in Figure 80 and Figure 81.

The 3D image in Figure 80 shows very clearly that the static air pressure gradient is the largest negative at the bottom of the chimney and decreases steadily throughout the chimney towards the top. The pressure at the bottom in the chimney flue is lower (the lowest) than the ambient pressure, which creates the draft. The pressure gradient decreases through the output and extension again as the energy source is removed.
Figure 81 (full front view section) of the solar plant shows the same result. The image also shows that the base plate, although it is very small and not functioning as a solar collector, supports an increase in the gradient of the static air pressure in the lower third of the flue towards the sides (away from the centre) of the solar power plant.

Figure 80: 3D Colour contour graph of static air pressure within the solar chimney as simulated in ANSYS.

Figure 81: 3D contour graph of static air pressure within the solar chimney as simulated in ANSYS (front view full section).
Figure 82 shows the association between static air pressure at defined height intervals within the chimney. The figure indicates that the flue pressure increases with height in the chimney and approaches the largest value at the outlet (2 m). The pressure then lowers towards the ambient value in the extension, and reduces and oscillates close to ambient pressure after it passed through the venture tube.

![Summer's Day Static Air Pressure](image)

Figure 82: Graphic presentation of static air pressure in the flue at different height intervals as simulated in ANSYS.

Figures 80, 81 and 82 indicate that the simulation results of static air pressure inside the flue supports the mechanism that controls the flow of air which is called the "natural draught", "natural ventilation", "chimney effect", or "stack effect".

4.6.1.2 Velocity in Y direction (upwards)

The vertical velocity of the air flow inside the flue is created by the rate at which the air flows into the chimney of the pilot plant through the inlet aperture at the bottom. The velocity inside the solar power plant is determined by the rate of change of the vertical movement of the air at a specific position inside the chimney. The simulated velocity differences for a summer’s day are presented in the 3D image (Figure 83).
Figure 83 and Figure 84 show that the velocity is the lowest at the bottom of the chimney. The figures show that the air accelerates against gravity and the velocity increases from the inlet vertical in the flue to turn the turbine at the top of the chimney, where the air velocity is the largest. In the front view full section of the solar power plant (Figure 84) it is also clear that the velocity increases through the pilot plant upwards to turn the turbine.

Figure 84: 3D contour graph of the air velocity within the solar chimney as simulated in ANSYS (front view full section).
Figure 85 shows the association between vertical air velocities at defined height intervals within the chimney. The figure indicates that the velocities increase with height in the chimney and approach a maximum value at the outlet into the extension and decrease very rapidly through the extension into the atmosphere.

Figures 83, 84 and 85 indicate that the simulation results of air velocities inside the flue support the mechanism that controls the air flow, which is called the "natural draught", "natural ventilation", "chimney effect", or "stack effect".

Figure 85: Graphic presentation of vertical air velocity in the flue at different height intervals as simulated in ANSYS.

**4.7.1.3 Static Air Temperature (Kelvin)**

The static air temperature of the air inside the chimney is due to the heat absorbed from the solar radiation of the sun by the steel plates of which the chimney is manufactured. As a result, the warmer air of a summer’s day is flowing through the solar power plant. The simulated static air temperatures are presented in Figure 86. This 3D contour graph shows that the static air temperature inside the solar power plant is higher than ambient temperature.
Figure 86: 3D contour graph of static air temperature contours inside the chimney as simulated in ANSYS.

Figure 87 shows full front view section of the solar power plant. It shows that the temperature is the largest at the bottom of the chimney. This is due to the fact that the base plate also absorbs heat from the solar radiation and stimulates the flow of hot air through the solar power plant, although it is not meant to be a solar collector. The temperature decreases slightly upwards through the chimney of the solar power plant, due to the movement of heated air inside the solar power plant. The influence of the base plate on the temperature can also be seen at the bottom of the chimney.

Figure 87: 3D graph of static air temperature contours simulated in ANSYS (front view full section).
Figure 88: Graphic presentation of static air temperature at height intervals simulated in ANSYS.

Figure 88 shows that the static air temperature first decreases sharply as it enters the chimney and increases steadily upwards towards the outlet of the chimney at 2 m. It then decreases sharply into the extension towards the atmosphere. After the outlet it decreases sharply and stabilises to be equal to the ambient temperature. Figures 86, 87 and 88 indicate that the temperature changes according to the expected hot air flow through the inside of the solar power plant.

4.7.1.4 Air Density

The heating of air inside and at the bottom of a chimney causes the lowering of the air density at the bottom. The lowering of the air density at the inside and at the bottom of the chimney causes this air to rise towards the top and is one of the causes for the chimney up draught. Air density variations in the power plant are associated with variations of temperature throughout the chimney.

The simulations in ANSYS (Figure 89 and Figure 90) show the density variations through the chimney. Figure 90 shows that the largest densities are obtained at the sides of the chimney. The lowest densities are obtained in the middle of the chimney due to the fact that the temperature transfer to the air increases the temperature and thus lowers the density.
Figure 89: 3D contour graph of air density as simulated in ANSYS.

Figure 90 shows the density variations in the 3D image of the full front view of the solar plant. The image shows that the density of the air is the lowest in the middle of the flue and that the density increases towards the sides of the chimney. It also shows that the air density outside the solar power plant is significantly higher than inside.

Figure 90: Graphic presentation of air density at height intervals simulated in ANSYS (front view full section).
The behaviour of the density distribution through the chimney should be viewed in conjunction with Figure 87, which depicts the temperature distribution through the chimney. The lowest air densities (Figure 90) are directly associated with the highest temperatures in the chimney (Figure 87). The air densities also increase slightly through the solar chimney upwards as the temperature decreases. The same association can also be made between the air density and the pressure inside the chimney (Figure 81), although not as profound.

Figure 91 presents the air densities in the flue at the defined height intervals inside the chimney. The figure shows that air density initially increases slightly at the inlet and slowly decreases upwards through the chimney towards the outlet at 2 m. The air density then steeply increases as expected into the outlet above 2 m into the extension, due to the fact that the air pressure is now at ambient pressure and temperature. After that it stabilises to reach the ambient air density.

Figure 91: Graphic presentation of air density at height intervals simulated in ANSYS.

4.7.1.5 Total Energy

The Total energy is the combination of kinetic energy and enthalpy. The kinetic energy in this case is dependent on the mass and the velocity of the moving air inside the chimney. The enthalpy is the heat energy contained in the heated air,
which causes the movement of the air from one height interval to the next. The combined energy turns the turbine to generate electrical power.

Figure 92 shows a 3D graph of the enthalpy numerical modelling results as obtained from the ANSYS software. It depicts the larger enthalpy inside the solar power plant due to the temperature of heated air.

The behaviour of the enthalpy distribution through the chimney should be viewed in conjunction with Figure 87, which depicts the temperature distribution through the chimney. The high enthalpies (Figure 93) in the middle of the chimney are directly associated with the highest temperatures in the chimney (Figure 87).

The enthalpy also decreases slightly through the solar chimney upwards as the temperature decreases. However the total energy increases as the kinetic energy increases upwards.

Figure 92: Graphic 3D presentation of enthalpy in the chimney as simulated in ANSYS.
The full front view section (Figure 93) shows that the enthalpy decreases through the solar power plant upwards according to the movement of heated air inside the solar power plant and correlates with the temperature distribution inside the chimney.

![Figure 93: Graphic presentation of the enthalpy distribution inside the chimney as simulated in ANSYS (front view full section).](image)

Figure 93 shows the enthalpy at defined height intervals inside the chimney. The graph clearly shows that the enthalpy decreases towards the top of the extension and stabilizes from 0.5 m towards 2 m at the outlet. There is a sharp decrease in the enthalpy at 2 m when the heated air flows through the outlet into the extension into the ambient atmosphere. The enthalpy increases in the chimney as the temperature of the air increases due to the solar radiation. At 2 m (outlet) the energy is adiabatically extracted from the air by the turbine. Lastly the enthalpy decreases again sharply into the extension as the air is circulated back into the atmosphere.
The graph in Figure 95 shows a steady increase of the kinetic energy of the air at in the inlet of 0.3 m to 1 m of the chimney. The kinetic energy then increases sharply towards the outlet at 2 m, where the flow area is the smallest. It sharply decreases as it enters the extension and the atmosphere from the outlet of the chimney. This is the venturi effect from the outlet into the outlet funnel, and behaves as expected.
The graph in Figure 96 shows the total energy (enthalpy and kinetic energy) at the different intervals inside the solar power plant. Again, the shape of the total energy graph is practically identical to that of the enthalpy, showing that the contribution of the kinetic energy to the total energy inside the solar power plant is insignificant.

Figure 96: Graphic presentation of the total energy in the chimney at different height intervals.
5. EXPERIMENTAL INVESTIGATION OF THE SELECTED SOLAR CHIMNEY SYSTEM

5.1 Construction of the Solar Chimney

The chimney pilot plant was manufactured in the mechanical workshop at the Faculty of Engineering according to the specifications in Table 41 and Figure 97. The dimensions used for the construction of the pilot plant were identical to what was used in the ANSYS numerical simulation software, to allow direct comparisons between the numerical simulations and the performance of the pilot plant.

The chimney was constructed with 20 mm square steel tubing in the octagon shape, as described in chapter 3. The chimney was constructed in five different sections (Figure 98), which allowed for easy transportation of the chimney towards the roof of the building where the pilot plant was operated. The sides of the chimney were covered with 2 mm mild steel plates, and were painted matt black to absorb the most possible solar radiation energy at a low wind speed. The different sections of the chimney were then assembled on the roof to obtain the final solar chimney power plant (Figure 99). The completed solar plant on the roof is shown in Figure 100.

Table 41: Explanation of symbols and dimensions used for the construction:

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Explanation</th>
<th>Physical dimensions</th>
</tr>
</thead>
<tbody>
<tr>
<td>D_c</td>
<td>Bottom diameter of the chimney</td>
<td>2.4 m</td>
</tr>
<tr>
<td>d_c</td>
<td>Top outlet diameter of the chimney</td>
<td>0.28 m</td>
</tr>
<tr>
<td>L_c</td>
<td>Height of the chimney</td>
<td>2 m</td>
</tr>
<tr>
<td>I</td>
<td>Inlet aperture</td>
<td>0.27 m</td>
</tr>
<tr>
<td>D_p</td>
<td>Steel plate diameter</td>
<td>4.00 m</td>
</tr>
<tr>
<td>L_e</td>
<td>Height of extension</td>
<td>0.57 m</td>
</tr>
<tr>
<td>D_e</td>
<td>Top diameter of extension</td>
<td>0.87 m</td>
</tr>
</tbody>
</table>
Figure 97: The solar chimney design that was modelled in the ANSYS Fluent simulation program.

Figure 98: One of the five different sections of the solar chimney pilot plant.
Figure 99: Assembly of the five different sections of the solar chimney pilot plant.

Figure 100: The completed pilot plant used in this study.
The next step was to mount the small turbine in the chimney outlet (Figure 101) and to connect the EL-WIN-USB Easy-Log data logger instrument to the turbine (Figure 102).

![Figure 101: The installed turbine in the outlet of the solar chimney.](image1)

The collected data was then transferred from the data logger every two weeks to a laptop computer (Figure 103) and the processed.

![Figure 102: The EL-WIN-USB Easy-Log data logger to take measurements.](image2)
Lastly, in addition measurements were taken with a few reflecting mirrors as well around the chimney to allow for solar radiation all around the chimney and to evaluate the increase in performance (Figure 104).

Figure 103: The EL-WIN-USB Easy-Log data logger connected to the computer.

Figure 104: The addition of reflective mirrors to increase the amount of solar radiation.
5.2 Measurement of the power output (performance) of the Chimney

The performance of the solar pilot was measured using an EL-WIN-USB Easy-Log data logger from LASCAR Electronics (Figure 102). The specific model used was the EL-USB-ACT, together with the windows software. The specifications of the data logger are:

- Compatible with AC and DC current clamps
- Energy monitoring mode (calculate power, cumulative energy and cumulative cost)
- AC and DC milli volt measurement mode
- Logging rates between 1s and 12hr
- 4mm banana plug inputs

When used with a current clamp, this standalone data logger measures and stores up to 127,232 AC and DC current readings over a 0 to 1000 amp DC measurement range (0 to 723 amps for AC). In “energy monitoring” mode, this data is converted into power, energy (using a user defined voltage value) and cost (using a user supplied energy unit cost). The milli volt measurement mode allows for direct measurement of voltage, up to 1V DC (700mV AC).

The user can easily set up the logger and view down loaded data by plugging the data logger into a PC’s USB port and using the supplied software. The software has provision for a clamp scaling factor (the clamp input-output ratio of amps to mill volts). Stored data can then be graphed, printed and exported to other applications. The high contrast LCD can show a variety of current, power, energy and cost information. At the touch of a button, the user can cycle between the most recent, maximum and minimum measurement values. The data logger is fitted with 2 replaceable AA batteries.

5.2.1 Data measurement

The performance of the pilot plant was monitored 24/7 for one year and the data was collected from the data logger every 14 days. The resolution of the data logger is 250 μV and 250 mA. The data logger took a measurement every 1s. Every 15 samples (every 15 seconds) were averaged and reported as one value in excel.
Measurements were recorded through the year to evaluate the performance of the pilot plant through seasonal changes. The following section is a discussion about the conditions of some of the different months of the year in Pretoria.

5.2.2 Data capturing months discussed for this project in Pretoria

January in Pretoria is in the middle of summer and the daily average maximum temperatures are 29°C with the average minimum 15°C, while in June the average maximum temperature is 20°C with a minimum of 1°C. The wettest month for Pretoria is in December with an average of 112.1 mm of precipitation falling while the driest month is July with 1.5 mm of rain. (http://www.myweather2.com/City-Town/South-Africa/Pretoria/climate-profile.aspx)

The first month discussed is April and is in autumn. Throughout April, daytime temperatures generally reach almost 25°C. At night the average minimum temperature drops to around 13°C. The average daily relative humidity in April is 62%. In April, the average expected hours that the sun will shine is 8 hours 45 min per day. The average daily wind speed in April is 3 km/h (http://www.myweather2.com/City-Town/South-Africa/Pretoria/climate-profile.aspx?month=4).

Throughout the month of May (late autumn) daytime temperatures will generally reach highs of 24°C. At night the average minimum temperature can be as low as 8°C. The average daily relative humidity for May is 55%. During May the expected average hours that the sun will shine is 9 hours 20 min per day. The average daily wind speed in May has been 3 km/h. (http://www.myweather2.com/City-Town/South-Africa/Pretoria/climate-profile.aspx?month=5).

During the month of August (late winter) daytime temperatures will generally reach highs of 24°C. At night the average minimum temperature can be as low as 8°C. The average daily relative humidity for August is 44%. In August the expected sun shine hours are on average 11 hours 14 minutes per day. The average daily wind speed in August is 5 km/h. (http://www.myweather2.com/City-Town/South-Africa/Pretoria/climate-profile.aspx?month=8)
The month of November is late spring and the average daytime temperatures will generally reach maximums of 29°C. At night the average minimum temperature can be as low as 16°C. The average daily relative humidity for November is 57%. They day can 30% of the time be overcast. The expected average sunshine hours for November are 11 hours per day. The average daily wind speed in November for Pretoria is 6 km/h (http://www.myweather2.com/City-Town/South-Africa/Pretoria/climate-profile.aspx?month=11).

5.3 Measured results for the Pilot Plant

Examples of the actual data measured from the pilot plant in Pretoria will be discussed in this section. The data measured by the data logger were the voltage (V) and the energy in watts (W). The examples of the results shown were for the pilot plant, firstly without the extra reflective mirrors and secondly with the reflective mirrors. Results are shown for a typical winter’s day, and typical summer’s day.

5.3.1 Pilot plant results without mirrors

5.3.1.1 Winter’s day in Pretoria

The mean climatic values for an average winter’s day (10 July) in Pretoria are given in Table 42. The highest voltages were between 10:00 and 11:00 because of temperature of nearly 23°C and later between 21:00 and 00:00 because of nearly 11.5 km/h wind speed.

Table 42: Mean climatic values for a winters day in Pretoria

<table>
<thead>
<tr>
<th>Day</th>
<th>T</th>
<th>TM</th>
<th>Tm</th>
<th>SLP</th>
<th>H</th>
<th>PP</th>
<th>VV</th>
<th>VE</th>
<th>VM</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>14.1</td>
<td>23</td>
<td>10</td>
<td>-</td>
<td>66</td>
<td>3.56</td>
<td>10.9</td>
<td>11.5</td>
<td>16.5</td>
</tr>
</tbody>
</table>

Figure 105 shows the original voltage data for a winter’s day (10 July). The graph shows that the maximum voltage was recorded during the daytime between 06H00 in the morning to 14H00 in the afternoon. Some quiet times are also shown of which the longest was between 14H00 to 18H00 in the afternoon, mainly because of overcast conditions. The larger active period between 20H00 and 24H00 was due to the wind associated with a thunderstorm.
Figure 105: Voltage data recorded for a winter’s day.

The data displayed in Figure 106 is the voltage for a winter’s day at every 15 minutes.

Figure 106: Voltage data for a winter’s day displayed at every 15 minutes.
The next parameter that was recorded over time for the pilot plant was the power output (Figure 107). The mean climatic values for an average winter’s day (8 August) in Pretoria are given in Table 43. The largest power distributions were between 08:00 in the morning and 14H30 in the afternoon because of temperature of nearly 19°C and a wind speed of 0.0 km/h.

Table 43: Mean climatic values for a winters day in Pretoria

<table>
<thead>
<tr>
<th>Day</th>
<th>T</th>
<th>TM</th>
<th>Tm</th>
<th>SLP</th>
<th>H</th>
<th>PP</th>
<th>VV</th>
<th>VE</th>
<th>VM</th>
<th>VG</th>
</tr>
</thead>
<tbody>
<tr>
<td>8</td>
<td>13.5</td>
<td>19</td>
<td>8</td>
<td>-</td>
<td>45</td>
<td>0</td>
<td>-</td>
<td>16.3</td>
<td>25.9</td>
<td>48.2</td>
</tr>
</tbody>
</table>

Figure 107 shows the original power data for a winter’s day (8 August). The graph shows that the maximum power was recorded during the daytime between 11:00 in the morning to 13:00 in the afternoon.

The quiet times are also shown between 19:00 in the evening to 06:00 in the morning, which is to be expected as the sun was not shining.

Figure 107: Power output data recorded for a winter’s day.

The data displayed in Figure 108 is the power output for a winter’s day at every 15 minutes.
Figure 108: Power output data for a winter’s day displayed at every 15 minutes.

5.3.1.2 Summer’s Day in Pretoria

The mean climatic values for a summer’s day (10 April) in Pretoria are given in Table 44. The highest voltages were between 10:00 and 14:00 because of temperature of nearly 31.4°C and later between 21:00 and 00:00 because of nearly 11.5 km/h wind speed.

Table 44: Mean climatic values for a summer’s day in Pretoria

<table>
<thead>
<tr>
<th>Day</th>
<th>T</th>
<th>TM</th>
<th>Tm</th>
<th>SLP</th>
<th>H</th>
<th>PP</th>
<th>VV</th>
<th>VE</th>
<th>VM</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>20.9</td>
<td>31.4</td>
<td>12.8</td>
<td>-</td>
<td>35</td>
<td>0</td>
<td>10.3</td>
<td>7.4</td>
<td>20.6</td>
</tr>
</tbody>
</table>

Figure 109 shows the original voltage data for a summer’s day (10 April). The graph shows that the maximum voltage was recorded during the daytime between 06H00 in the morning to 14H00 in the afternoon.

Some quiet times are also shown of which the longest was between 14H00 to 18H00 in the afternoon, mainly because of overcast conditions. The larger active period between 20H00 and 24H00 was due to the wind associated with a thunderstorm, which carried on intermittently from 01H00 to 03H00 in the morning. The rest of the early morning was quiet.
The data displayed in Figure 110 is the voltage for a summer’s day at every 15 minutes. The average voltage output of a summer’s day is two times more than for a winter’s day (Figure 107).

Figure 109: Voltage data recorded for a summer’s day.

Figure 110: Voltage output for a summer’s day displayed at every 15 minutes.
Figure 111: Power output data recorded for a summer's day.

Figure 111 shows the original power data for a summer’s day (28 April). The graph shows that the maximum power was recorded during the daytime between 11:00 in the morning to 14:00 in the afternoon. A strong thunderstorm associated with wind was recorded between midnight, 0H00 and 06H00 in the morning. The quiet times are also shown between 17:00 in the evening to midnight, which is to be expected as the sun was not shining.

Figure 112: Power output for a summer’s day displayed at every 15 minutes.
The data displayed in Figure 112 is the power output for a summer’s day at every 15 minutes. The power output for a summer’s day is about twice the power output of a winter’s day (Figure 108).

5.3.2 Pilot plant results with mirrors
Although simulation results were not obtained for the solar up draught chimney with mirrors (Figure 113), results were obtained during the measuring phase, to prove that the performance of the plant will increase if mirrors were added.

The reason for this is that the mirrors reflected solar radiation onto the sides of the chimney that would normally not receive direct radiation and heated the chimney from all sides.

Figure 113: Solar chimney pilot plant with mirrors.
5.3.2.1 Winter’s day in Pretoria

The mean climatic values for a winter’s day (20 July) in Pretoria are given in Table 45. The highest voltages were between 10:30 and 17:30 because of temperature of nearly 22°C and later between 22:00 and 00:00 because of some wind.

Table 45: Mean climatic values for an average winters day in Pretoria

<table>
<thead>
<tr>
<th>Day</th>
<th>T</th>
<th>TM</th>
<th>Tm</th>
<th>SLP</th>
<th>H</th>
<th>PP</th>
<th>VV</th>
<th>VE</th>
<th>VM</th>
<th>VG</th>
<th>RA</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>10.3</td>
<td>22</td>
<td>8</td>
<td>-</td>
<td>89</td>
<td>8.64</td>
<td>10.6</td>
<td>6.7</td>
<td>16.5</td>
<td>37</td>
<td>89</td>
</tr>
</tbody>
</table>

Figure 114 shows the original voltage data with mirrors for a winter’s day (20 July). The graph shows that the maximum voltage was recorded during the daytime between 10:30 in the morning to 17:30 in the afternoon. Some quiet times are also shown of which the longest was between 18:00 to 20:00 in the evening, mainly due to lack of sun and overcast conditions. The larger active period was during mid day as expected.

Figure 114: Voltage data recorded for a winter’s day with mirrors.

The data displayed in Figure 115 is the voltage with mirrors for a winter’s day at every 15 minutes. The average voltage output with mirrors of a winter’s day is almost the same as for a winter’s day without mirrors (Figure 106).
The next parameter that was recorded for the pilot plant with mirrors was the power output (Figure 116). The mean climatic values for an average winter’s day (22 July in Pretoria) are given in Table 46. The largest power distributions were between 08:00 in the morning and 17:30 in the afternoon because of temperature of nearly 18°C and a wind speed of 10.0 km/h.

Table 46: Mean climatic values for a winter’s day in Pretoria

<table>
<thead>
<tr>
<th>Day</th>
<th>T</th>
<th>TM</th>
<th>Tm</th>
<th>SLP</th>
<th>H</th>
<th>PP</th>
<th>VV</th>
<th>VE</th>
<th>VM</th>
<th>VG</th>
</tr>
</thead>
<tbody>
<tr>
<td>22</td>
<td>13.3</td>
<td>18</td>
<td>9</td>
<td>-</td>
<td>69</td>
<td>0</td>
<td>10</td>
<td>10</td>
<td>27.8</td>
<td>13.3</td>
</tr>
</tbody>
</table>

Figure 116 shows the original power data with mirrors for a winter’s day (22 July). The graph shows that the maximum power was recorded during the daytime between 11:00 in the morning to 16:00 in the afternoon.

The quiet times are also shown between 19:00 in the evening to 06:00 in the morning, which is to be expected as the sun was not shining.
Figure 116: Power data recorded for a winter’s day with mirrors.

The data displayed in Figure 117 is the power output with mirrors for a winter’s day at every 15 minutes, which is less than the power output without mirrors (Figure 108). This mainly due to the lower power produced by the power plant between 15:00 in the afternoon and 19:00, due to overcast conditions. The peak between 18:00 and 19:00 was due to wind.

Figure 117: Power output with mirrors for a winter’s day displayed at every 15 minutes.
5.3.2.2 Summer’s day in Pretoria

The mean climatic values for a summer’s day (10 April) in Pretoria are given in Table 47. The highest voltages were between 10:00 and 17:00 because of the temperature of nearly 26 °C and later between 21:00 and 00:00 because of nearly 15.7 km/h wind.

Table 47: Mean climatic values for a summer’s day in Pretoria

<table>
<thead>
<tr>
<th>Day</th>
<th>T</th>
<th>TM</th>
<th>Tm</th>
<th>SLP</th>
<th>H</th>
<th>PP</th>
<th>VV</th>
<th>VE</th>
<th>VM</th>
<th>VG</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>19.9</td>
<td>26</td>
<td>13</td>
<td>-</td>
<td>52</td>
<td>-</td>
<td>10</td>
<td>15.7</td>
<td>24.1</td>
<td>-</td>
</tr>
</tbody>
</table>

Figure 118 shows the original voltage data for a summer’s day (10 April). The graph shows that the maximum voltage was recorded during the daytime between 12:00 and 16:00 in the afternoon.

Some quiet times are also shown between 02:00 and 08:30 in the morning as expected. The active period between 18:00 and 24:00 was due to the wind associated with a thunderstorm.

The data displayed in Figure 119 is the voltage for a summer’s day at every 15 minutes. The average voltage output of a summer’s day is about five (5) times more than for a summer’s day without mirrors (Figure 110).

Figure 118: Voltage data with mirrors recorded for a summer’s day.
Figure 119: Voltage output with mirrors for a summer’s day displayed at every 15 minutes.

Figure 120 shows the original power data for a summer’s day (10 November). Climatic data is shown in Table 48.

Table 48: Mean climatic values for a summer’s day in Pretoria

<table>
<thead>
<tr>
<th>Day</th>
<th>T</th>
<th>TM</th>
<th>Tm</th>
<th>SLP</th>
<th>H</th>
<th>PP</th>
<th>VV</th>
<th>VE</th>
<th>VM</th>
<th>VG</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>23.1</td>
<td>33.9</td>
<td>17</td>
<td>-</td>
<td>49</td>
<td>-</td>
<td>10</td>
<td>10.6</td>
<td>20.6</td>
<td>42.4</td>
</tr>
</tbody>
</table>

Figure 120: Power output data with mirrors recorded for a summer’s day.
The highest power was between daytime between 15:00 to 20:00 in the afternoon, due to a temperature of nearly 33.9 °C and a wind of nearly 10.6 km/h.

The data displayed in Figure 121 is the power output for a summer’s day with mirrors every 15 minutes. The power output for a summer’s day with mirrors is larger than the power output of a summer’s day without mirrors (Figure 108).

![Power output with mirrors for a summer’s day displayed at every 15 minutes.](image)

**Figure 121: Power output with mirrors for a summer’s day displayed at every 15 minutes.**

### 5.4 Comparison of the Results

The performance of the pilot plant was monitored continuously for 18 months. Data was collected with and without mirrors. Table 49 shows a summary of the results obtained.

<table>
<thead>
<tr>
<th>Mean Temp (°C)</th>
<th>Wind speed (km/h)</th>
<th>Voltages (Max-mV)</th>
<th>Voltages (Min-mV)</th>
<th>Power (Max-mW)</th>
<th>Power (Min-mW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pilot plant without mirrors</td>
<td>Winters Day</td>
<td>13.8</td>
<td>13.9</td>
<td>101.2</td>
<td>0.2</td>
</tr>
<tr>
<td></td>
<td>Summers Day</td>
<td>20.6</td>
<td>5.5</td>
<td>122.2</td>
<td>0.2</td>
</tr>
<tr>
<td>Pilot plant mirrors</td>
<td>Winters Day</td>
<td>11.8</td>
<td>8.35</td>
<td>102.2</td>
<td>0.2</td>
</tr>
<tr>
<td></td>
<td>Summers Day</td>
<td>21.5</td>
<td>13.15</td>
<td>202.6</td>
<td>0.2</td>
</tr>
</tbody>
</table>
Table 49 shows that the pilot plant without mirrors produced 70% more power in the summer than in the winter. The pilot plant with mirrors in the summer produced 250% more power than the pilot plant without mirrors and 430% more power than the pilot plant in the winter without mirrors (Figure 125).
CHAPTER 6

6. DISCUSSION OF RESULTS

This performance of the solar power plant, which was the focus of this research project, was evaluated by generating three different sets of data. These were:

- Theoretical and numerical simulation performance results using the ANSYS software.
- The long term measurement of the performance of the constructed pilot plant with a data logger (voltage and power). The physical dimensions of the pilot plant were exactly the same as with the numerical simulations to allow a direct comparison between the two data sets.
- Lastly, measurements (voltage and power) of the constructed pilot plant with mirrors were also performed, although it was not simulated in ANSYS. This was done because it was a relatively easy task to construct the mirrors, and the data measuring system was in place.

The comparison of the simulation results with pilot plant results are at the top of chimney where turbine was placed. The turbine efficiency used was 80%.

6.1 Discussion of results without mirrors

6.1.1 Discussion of simulations results without mirrors

During the numerical simulations of the pilot plant without mirrors, two different situations were evaluated. These were for a winter’s day and a summer’s day. There parameters used are summarised in Table 50.

Certain performance parameters of the pilot plant were also evaluated and compared during the simulations for these days, and were:

- Static pressure (Pascal)
- Velocity in Y direction (up flow) (m/s)
- Air density (kg/m$^3$)
- Static temperature (Kelvin)
- Total energy
Table 50: Comparison of the parameters used during the numerical simulations in ANSYS

<table>
<thead>
<tr>
<th></th>
<th>Winter’s day</th>
<th>Summer’s day</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature</td>
<td>17 °C</td>
<td>38 °C</td>
</tr>
<tr>
<td>Steel Plate Temperature</td>
<td>30 °C</td>
<td>60 °C</td>
</tr>
<tr>
<td>Pressure (Atmosphere)</td>
<td>101.325 kPa</td>
<td>101.325 kPa</td>
</tr>
<tr>
<td>Wind speed</td>
<td>0 m/s</td>
<td>0 m/s</td>
</tr>
<tr>
<td>Materials</td>
<td>Steel and atmospheric air</td>
<td>Steel and atmospheric air</td>
</tr>
<tr>
<td>Air Density</td>
<td>1.216534 kg/m³</td>
<td>1.134428 kg/m³</td>
</tr>
<tr>
<td>Gravity Acceleration</td>
<td>X Axis 0 m/s²</td>
<td>X Axis 0 m/s²</td>
</tr>
<tr>
<td></td>
<td>Y Axis -9.81 m/s²</td>
<td>Y Axis -9.81 m/s²</td>
</tr>
<tr>
<td></td>
<td>Z Axis 0 m/s²</td>
<td>Z Axis 0 m/s²</td>
</tr>
</tbody>
</table>

The simulated electrical power output of the pilot plant (without mirrors) is calculated as follows:

\[ \text{Power (P)_{electrical}} = n \times \text{Power (P)_{maks}} \]  
(6.1)

The radius of the turbine blades was shorter than the radius of the chimney outlet, and swept only 80% of the chimney outlet area (www.cray.com). The factor \( n \) accounts for this and is 0.8, but

\[ P_{\text{maks}} = \Delta P - Q \]  
(6.2)

Where \( \Delta P \) is the pressure gradient and \( Q \) is the heat flow. However

\[ \Delta P = P_{\text{static}} + 0.5 \rho V^2 \]  
(6.3)

Where \( V \) is the air velocity in the chimney and \( \Delta \) is the density of the air column.

The numerical simulated performance results for the pilot plant without mirrors are given in Table 51. The results are also shown in Figure 122.
Table 51: Comparison of the results obtained during the numerical simulations in ANSYS

<table>
<thead>
<tr>
<th></th>
<th>Winter’s day</th>
<th>Summer’s day</th>
</tr>
</thead>
<tbody>
<tr>
<td>Area (m²)</td>
<td>0.12</td>
<td>0.12</td>
</tr>
<tr>
<td>Air Density (kg/m³)</td>
<td>1.2</td>
<td>1.11</td>
</tr>
<tr>
<td>Static Pressure (Pa)</td>
<td>-0.044</td>
<td>-0.08</td>
</tr>
<tr>
<td>Velocity (m/s)</td>
<td>2.1</td>
<td>2.67</td>
</tr>
<tr>
<td>Total Pressure (Pa)</td>
<td>2.44</td>
<td>3.73</td>
</tr>
<tr>
<td>Total Power (mW)</td>
<td>26.90</td>
<td>40.48</td>
</tr>
<tr>
<td>Power (Electrical)</td>
<td>15.56</td>
<td>23.45</td>
</tr>
</tbody>
</table>

Figure 122: Simulated Power output without mirrors for the pilot plant.

The results showed that the power output increases as the temperature increases and that the output of the plant is the largest in summer, as expected.

6.1.2 Discussion of measured results without mirrors

Real measurements of the pilot plant without mirrors for the two different situations were evaluated. The data captured by the data logger was voltage and the power output. The temperature and wind speed were received from weather data history. These were for a winter’s day, and a summer’s day. There parameters used are summarised in Table 52. The results are also shown in Figure 123.
Table 52: Comparison of the measure results of the pilot plant without mirrors.

<table>
<thead>
<tr>
<th></th>
<th>Mean Temperature (°C)</th>
<th>Wind speed (km/h)</th>
<th>Power (Max) (mW)</th>
<th>Power (Minimum) (mW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Winters Day</td>
<td>19</td>
<td>13.9</td>
<td>15.181</td>
<td>0.048</td>
</tr>
<tr>
<td>Summers Day</td>
<td>27</td>
<td>5.5</td>
<td>25.724</td>
<td>0.048</td>
</tr>
</tbody>
</table>

The results showed that the power output increases as the temperature increases and that the output of the plant is the largest in summer, as expected. The comparison between the theoretical simulations and the measured data from the pilot solar plant without mirrors indicate that the predicted power generated by the pilot plant were similar to the actual values measured.

### 6.2 Discussion of results with mirrors

Data was also gathered from the pilot plant with the addition of mirrors to increase the flux of solar radiation. The pilot plant with mirrors was not numerically simulated in ANSYS, and this was done purely because the opportunity was available. The mirrors around the pilot plant increased the solar radiation and the temperature
around the chimney. This increased the power output of the system. The results for
the power plant with mirrors are shown in Table 53. The results are also shown in
Figure 124.

Table 53: Comparison of the measure results of the pilot plant with mirrors.

<table>
<thead>
<tr>
<th></th>
<th>Mean Temp (°C)</th>
<th>Wind speed (km/h)</th>
<th>Power (Max) (mW)</th>
<th>Power (Min) (mW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Winters Day</td>
<td>18</td>
<td>8.35</td>
<td>4.344</td>
<td>0.048</td>
</tr>
<tr>
<td>Summers Day</td>
<td>33.9</td>
<td>13.15</td>
<td>65.279</td>
<td>0.048</td>
</tr>
</tbody>
</table>

Figure 124: Measured power output with mirrors of the pilot plant.

6.3 Comparison of the results

The comparison of the results is shown in Figure 125. It shows that the results of the
simulated and measured pilot plant without mirrors are in agreement, when all the
efficiencies are taken into account. As expected the results of the pilot plant with
mirrors are much larger due to the increased radiation, heat flow and temperature.
Figure 125: Comparison of all the power generated results of the pilot plant.
CHAPTER 7

7. CONCLUSIONS AND RECOMMENDATIONS

7.1 Conclusion

The shortage of alternative renewable energy sources can be eliminated. It will, however, take time, money, and a combined effort on the part of many scientists and sponsors. Moreover, the major challenge will be to convince governments that competition for the established energy sources and industries will not affect their income; it will just be in a different form.

This research into the development and performance evaluation of a solar chimney power generation system confirmed this new mind set. It indicated that solar energy is a viable stable option for power generation, while limiting the production of gases attributing to the greenhouse effect.

The results showed that a good correlation exists between the theory, numerical simulations and the actual data measured from the pilot solar chimney plant. Comparison between the simulations and data from the pilot solar chimney plant without mirrors indicated that the results were very similar. Mirrors are used to heat the pilot solar chimney plant from all angles. The data obtained from the pilot solar chimney plant with mirrors support the conclusion that any solar chimney plant will generate power, if the following aspects are considered in the design:

- The flow of the air (fluid) is incompressible,
- The flow upstream of the air is steady and uniform,
- There is no rotational flow or turbulence produced by the air,
- The air velocity is steady and uniform,
- The flow upstream is contained by the boundary stream tube (chimney),
- Maintenance,
- Space and area of installation,
- The weather will play a roll (rust, wear and tear, ext.).
This type of power generation plant can function where wind is absent and is also less destructive on the bird and bat populations.

These power plants should be employed to generate power, especially in areas where sunshine is abundant and wind potential is low. It will contribute towards the protection of the atmosphere and the environment.

7.2 Recommendation

Larger demonstration plants must be constructed for future use to deliver towards the energy needs of the planet. Smaller plants that have the capacity to supply one or two households with electricity should be constructed first. In this section, simulation results are presented for 10 kW and 20 kW systems.

This research showed that there is a good comparison between the simulated results and the measured results of the plant (Chapter 3 to 5). A demonstration plant would operate through the year and average conditions were used for the simulations. We therefore assume that the simulations for 10 kW and 20 kW systems in the ANSYS software will yield a realistic indication of a demonstration plant design (Figures 126 and 127).

Figure 126: Model of a demonstration plant in ANSYS.
Figure 127: Enlarged side view of the demonstration plant showing the sloping collector.

### 7.2.1 Simulations for a 10 kW Plant

The point of departure for simulations in ANSYS that will produce 10 kW of energy (for one household) is that the design specifications and sizes of the 10 kW wind generator are fixed. As an example the specifications (Table 54) of the Wind Energy Resources (WER) turbines are used (http://wind-energy-resources.com).

A deliberate decision was taken to limit the height of the chimney to 60 m, because it is a reasonable easy construction height to achieve without excessive construction costs.
Table 54: Specifications for the WER 10 kW turbine

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model</td>
<td>FD7.5-10/10</td>
</tr>
<tr>
<td>Rotor Diameter</td>
<td>7.5 m</td>
</tr>
<tr>
<td>Working Wind Speed</td>
<td>3-25 m/s</td>
</tr>
<tr>
<td>Cut-in Wind Speed</td>
<td>3 m/s</td>
</tr>
<tr>
<td>Rated Wind Speed</td>
<td>10 m/s</td>
</tr>
<tr>
<td>Survival Wind Speed</td>
<td>50 m/s</td>
</tr>
<tr>
<td>Rated Output Power</td>
<td>10 kW</td>
</tr>
<tr>
<td>Maximum Output Power</td>
<td>12.4 kW</td>
</tr>
<tr>
<td>Rated Output Voltage</td>
<td>DC 460 V</td>
</tr>
</tbody>
</table>

The most important parameter on which the design is based is the rotor diameter (Table 54). The rotor diameter will determine the diameter of the chimney outlet. The next important parameter is the rated wind speed specified for the turbine (Table 54), at which the turbine will function optimally. These specifications determined the actual sizes of the rest of the design (Table 55), within the boundaries of the original pilot plant design (Figure 128).

Table 55: Actual sizes of the 10 kW demonstration plant.

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Explanation</th>
<th>Physical dimensions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dc</td>
<td>Bottom diameter of the chimney</td>
<td>50 m</td>
</tr>
<tr>
<td>dc</td>
<td>Top outlet diameter of the chimney</td>
<td>8 m</td>
</tr>
<tr>
<td>Lc</td>
<td>Height of the chimney</td>
<td>60 m</td>
</tr>
<tr>
<td>I</td>
<td>Inlet aperture</td>
<td>6 m</td>
</tr>
<tr>
<td>Dc</td>
<td>Diameter of collector</td>
<td>400 m</td>
</tr>
<tr>
<td>Ci</td>
<td>Collector inlet</td>
<td>3 m</td>
</tr>
<tr>
<td>Le</td>
<td>Height of extension</td>
<td>13 m</td>
</tr>
<tr>
<td>De</td>
<td>Top diameter of extension</td>
<td>11 m</td>
</tr>
</tbody>
</table>
The case simulated a typical average day in Pretoria. The following parameters were used in ANSYS simulation, based on a rated velocity of at least 10 m/s (Table 54):

- Ambient temperature: 25°C
- Steel Plate Temperature: 40°C
- Pressure (Atmospheric): 101.325 kPa
- Wind speed: 0 m/s
- Materials: Steel and atmospheric air
- Air Density: 1.183892 kg/m³
- Gravitational Acceleration
  - X Axis: 0 m/s²
  - Y Axis: -9.81 m/s²
  - Z Axis: 0 m/s²

Figure 128: The solar chimney design simulated in the ANSYS Fluent Simulation Program for the demonstration solar plant.
The simulated velocity obtained for this size of the pilot plant in ANSYS is 10.039 m/s, and is shown in Figure 129.

Figure 129: Simulated air velocity results for a 10 kW system.

### 7.2.2 Simulations for a 20 kW Plant

The point of departure for simulations in ANSYS that will produce 20 kW of energy (for two households) is that the design specifications and sizes of the 20 kW wind generator are fixed. As an example the specifications (Table 56) of the Polaris turbines are used (http://www.polarisamerica.com/turbines/20kw-wind-turbines).

<table>
<thead>
<tr>
<th>Table 56: Specifications for the Polaris 20 kW turbine</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Polaris – 20 kW wind turbine</strong></td>
</tr>
<tr>
<td>Rated Power</td>
</tr>
<tr>
<td>Rotor Diameter</td>
</tr>
<tr>
<td>Rated Wind Speed</td>
</tr>
<tr>
<td>Cut-in Speed</td>
</tr>
<tr>
<td>Cut-out Speed</td>
</tr>
<tr>
<td>Survival Wind Speed</td>
</tr>
<tr>
<td>Operational RPM</td>
</tr>
</tbody>
</table>
The most important aspect on which the design parameters are based is the rotor diameter (Table 56). The rotor diameter will determine the diameter of the chimney outlet. The next important parameter is the rated wind speed specified for the turbine (Table 56), where the turbine will function optimally. These specifications determined the actual sizes of the rest of the design (Table 57), but within the boundaries of the original pilot plant design (Figure 128).

The outlet diameter of the chimney is 10.5 m for the 20 kW system while the outlet diameter for the 10 kW system was only 8 m.

Table 57: Actual sizes of the 20 kW demonstration plant.

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Explanation</th>
<th>Physical dimensions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dc</td>
<td>Bottom diameter of the chimney</td>
<td>60 m</td>
</tr>
<tr>
<td>dc</td>
<td>Top outlet diameter of the chimney</td>
<td>10.5 m</td>
</tr>
<tr>
<td>Lc</td>
<td>Height of the chimney</td>
<td>60 m</td>
</tr>
<tr>
<td>I</td>
<td>Inlet aperture</td>
<td>7.5 m</td>
</tr>
<tr>
<td>Dc</td>
<td>Diameter of collector</td>
<td>420 m</td>
</tr>
<tr>
<td>Ci</td>
<td>Collector inlet</td>
<td>3.75 m</td>
</tr>
<tr>
<td>Le</td>
<td>Height of extension</td>
<td>16.5 m</td>
</tr>
<tr>
<td>De</td>
<td>Top diameter of extension</td>
<td>14.5 m</td>
</tr>
</tbody>
</table>

This case simulated a typical average day in Pretoria. The following parameters were used in the ANSYS simulation based on a rated velocity of at least 10 m/s (Table 57):

- Ambient temperature: $25^0$ C
- Steel Plate Temperature: $40^0$ C
- Pressure (Atmospheric): 101.325 kPa
- Wind speed: 0 m/s
- Materials: Steel and atmospheric air
- Air Density : 1.183892 kg/m$^3$
- Gravitational Acceleration
  - X Axis 0 m/s$^2$
  - Y Axis - 9.81 m/s$^2$
  - Z Axis 0 m/s$^2$
The velocity obtained from this simulation in ANSYS was 10.074 m/s, as shown in Figure 130.

![Simulated air velocity results for a 20 kW system.](image)

Figure 130: Simulated air velocity results for a 20 kW system.

A practical height for the manufacturing of the solar chimney power demonstration plant is sixty meters. The results from the simulations for the 10 kW and 20 kW systems suggest that to reach the optimal velocity of 10 m/s for each system with a practical chimney height, the size of the collector has to be varied to keep the height of the chimney as low as 60 m.
8. BIBLIOGRAPHY


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