Addis Ababa University Institute of Technology

School of Graduate Studies

Center for Renewable Energy Technology

Experimental Investigation on Cylindrical and Divergent Solar Chimney Power Plants

A thesis submitted to the school of graduate studies of Addis Ababa University Addis Ababa Institute of Technology in partial fulfillment for the Degree of Masters of Science in Renewable Energy Technology

By: - Hana Gebremariam

ID No. GSR/9013/14

Advisor: - Solomon Tesfamariam (PhD)

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CERTIFICATION

I, the undersigned, certify that I read and hereby recommend for acceptance by Addis Ababa University Institute of Technology, Center of Renewable Energy Technology a thesis entitled "Experimental Investigation on Cylindrical and Divergent Solar Chimney Power Plants". This certificate is used as a partial fulfillment of the requirement for the Masters of Science in Renewable Energy Technology.

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Name: Hana Gebremariam

Signature: ________________

Date: ________________

Advisor Name: Solomon Tesfamariam (PhD)

Signature: ________________

Date: ________________

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By: Hana Gebremariam

Approved by the Board of Examiners:

(Advisor)	Signature	Date
(Internal Examiner)	Signature	Date
(Internal Examiner)	Signature	Date
(Chairman)	Signature	Date
(Director of Post Graduate Program)	Signature	Date

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ABSTRACT

The solar updraft tower (SUT) is an innovative renewable energy power plant that converts low-temperature solar heat into electricity. This system operates by heating air beneath a large, greenhouse-style roof, which surrounds the base of a tall chimney. The heated air rises through the chimney, creating an updraft that drives wind turbines to generate electricity. This research evaluates the performance of a small-scale solar chimney power plant (SCPP) by developing two prototypes: one with a cylindrical chimney and another with a divergent chimney. The study focuses on analyzing the impact of chimney design on power output and efficiency using local solar radiation data. Experimental results reveal that the average power outputs for the cylindrical and divergent chimneys were 5.29 W and 23.6 W, respectively. The divergent chimney with a 2° angle achieved an efficiency of 1.9%, which is significantly higher than the 0.44% efficiency of the cylindrical chimney. These findings indicate that the area ratio and air velocity substantially influence the power plant's performance. Furthermore, theoretical calculations showed that increasing the chimney height from 1.5 meters to 2.5 meters led to a 66.6% increase in power output for both chimney types, while increasing the height from 2.5 meters to 3.5 meters resulted in a 40% increase. A 2.5-meter-high divergent chimney produced 3.1 times the power output compared to a 3.5-meter cylindrical chimney, and a 1.5-meter divergent chimney exhibited an 86.46% increase in power output compared to a 3.5-meter cylindrical chimney. Overall, the divergent chimneys enhanced power output by 335.4% at the same height, demonstrating the significant impact of chimney configuration.

Keywords: divergent chimney, cylindrical chimney, performance, power output.

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NOMENCLATURE

Symbols

A	Area, m^2
c_p	Specific heat capacity, J/kg.K
D	Diameter
G	Global solar radiation, W /m^2
g	Gravitational acceleration, m/s^2
H	Height, m
$\dot{m}$	Masse flow rate, kg/s
P	Power, W
$\dot{Q}$	Rate of heat transfer, W
ΔT	Change in Temperature, ^oC

Greek letters

η	Efficiency
ρ	Density, kg/m^3

Subscript

Coll	collector
Ch	chimney
cyl	Cylindrical
abs	Absorber
div	divergent
0	Collector inlet

1	Collector outlet
2	Chimney outlet
t	Turbine
ovl	Overall efficiency

Abbreviations

SCPP	Solar Chimney Power Plant
DA	Divergent Angle
AR	Air Ratio
CSCPP	Cylindrical Solar Chimney Power Plant
DSCPP	Divergent Solar Chimney Power Plant

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CHAPTER ONE

1 INTRODUCTION

1.1 Background

The exponential increase in energy consumption with population expansion implies that traditional energy sources may be insufficient to fulfill the world's expanding energy demands. As a result, renewable energy will become ever more vital.

Solar energy can be converted into electrical power using a variety of direct and indirect energy conversion devices. Solar photovoltaic cell is an example of a well-known technology for the direct conversion of solar energy into electrical energy. On the other hand, solar thermal power plants are a system that converts solar energy indirectly into electrical energy by using mechanical devices to drive electrical generators. For high-temperature power plants, solar concentrators like parabolic dish, parabolic trough, and heliostats are used to significantly increase the working fluid temperature. The solar chimney types of power plants can be taken as low-temperature solar thermal power plants. The three main components of the solar chimney are a collector, a chimney, and a turbine.

Solar Chimney Power Plants (SCPPs) operate on the principle of an air-draft mechanism that moves hot air upward and drives a mechanical turbine. The idea of an updraft has been used for centuries. The earliest one was envisioned by Leonardo da Vinci to draft hot air to roast food. The idea of SCPP was initially understood by Isidoro Cabanyes in 1903. Günther published the concept after him. Numerous inventions have been made since 1975 in the USA, Australia, Canada, Israel, and other nations [1][2]. As mentioned in figure 1.1 a prototype of 50 kW solar chimney power plant was first built by the 'Spanish utility Union Electrica Fenosa' in Manzanare in 1981–1982, Figure 2.1 [2][3]. The prototype has a collector diameter of 244 m and a chimney length of 194.6 m.

Figure 1.1First solar chimney power plant prototype in Manzanres [3]

The low conversion efficiency is the main challenge of SCPP. However, its low maintenance cost and simplicity of construction attract many researchers to focus on performance enhancement by varying the dimensions and configurations of its main components [4].

These findings underscore the need of doing experimental research to differentiate between cylindrical and divergent solar chimney power plants, as this allows for the optimization of their performance and prospective increases in power production. Furthermore, experimental examination provides the actual performance of the power plant with both the natural effect and the uncontrolled parameter impact. Hence the goal of this research is to ascertain how the efficiency of a solar chimney power plant is affected by the chimney design configuration between a conventional and divergent chimney. Creating a prototype for small-scale examination and using experimental analysis. Assessing the performance of the system as well[5]

1.2 Problem Statement

Solar Chimney Power Plants (SCPPs) operate on the principle of an air-draft mechanism that moves hot air upward and drives a mechanical turbine. These can be converted into electrical energy. Optimizing SCPP's layout is one way to improve its performance. Many researchers have reported their studies to improve the performance of the Solar Chimney Power Plant (SCPP) by varying the dimensions and configuration of the plant's main components [1]. The three main components of the SCPP are the solar collector (SC), which includes the glazing cover and absorber, the chimney, and the power conversion unit (PCU), which is mounted just after the SC.

The power plant's operating concept is the same regardless of the various chimney layouts. The size and shape of the chimney have a big impact on the plant's output of power. Although, in the case of divergent and convergent chimneys, the diameter of the chimney has a major impact on the system's power production. Comparatively speaking with other chimney designs, the effect is reduced with cylindrical chimneys. In a convergent tower, the top velocity increases while the mass flow rate drops, resulting in a kinetic energy that is comparable to that of a tower with a constant area.

Despite playing a significant influence in the performance of the plant, the impact of chimney design configuration is rarely examined, in contrast to chimney height and collector radius. According to a prior numerical study, the efficiency was 0.29% at the area ratio (AR) = 1, but climbed to 0.83% at AR = 4.1. It demonstrates the impact of inlet-to-outlet diameter of chimney on power plants performance. Furthermore, there are extensive studies on numerical data but insufficient experimental studies. Hence, this research work focuses on the experimental investigation of two SCPPs: one with a cylindrical chimney and the other with a divergent chimney to evaluate the performance.

As a result of this, the best chimney configuration needs to be defined by assessing the performance of two different designs of the chimney.

1.3 Objective

1.3.1 General objective

To conduct an experimental study for the performance evaluation of cylindrical and divergent solar chimney power plants.

1.3.2 Specific objective

- ✓ To design and develop models of solar chimney power plant.
- ✓ To conduct experiments and analyze the flow parameters on the developed prototype.
- ✓ To evaluate the setup’s performance characteristics based on their efficiencies and power outputs.
- ✓ To examine the effect of different configurations on the performance of the power plant.

- ✓ Compare the result with other researcher’s findings.

1.4 Scope of the Study

The performance of each constituent has its own effect on the power output of the power plant. Aside from that, the system evaluation and each other have a relationship, despite the fact that the study focuses on evaluating the effect of the cylindrical and divergent chimney design on efficiency of the power plant. By developing a small prototype and experimental analysis. Also, there are different type of divergent configuration but the linear conical type will be the focus. Furthermore, the analysis will focus on the experimental investigation of the chimney design effect on the power output and efficiency of the system instead of making a deep evaluation of each component.

1.5 Significance of the Study

The SCPP components' simple and long-lasting technologies make them accessible to technologically developing countries. Which are usually sunny and have a limited supply of raw materials. SCPPs do not necessitate the use of cooling water, combustible fuel, or extensive maintenance. The low SCPP conversion efficiency, as determined by the system's thermal performance, is a serious issue. Furthermore, it can only convert a small portion of the collected solar heat into electricity, resulting in a "low efficiency level." However, their low maintenance costs and inexpensive, durable construction make up for this disadvantage.

Despite the fact that the study will conduct an experimental investigation of a small-scale solar chimney power plant by developing two prototypes, a cylindrical chimney power plant and a divergent chimney power plant, with the local daily solar radiation, to show how the power output and efficiency affect by the design of chimney. The experiment's analysis results reveal the performance of the power plant in a practical situation, which is important for future research and filling a gap in this area of study.

CHAPTER TWO

2 LITERATURE REVIEW

2.1 Introduction

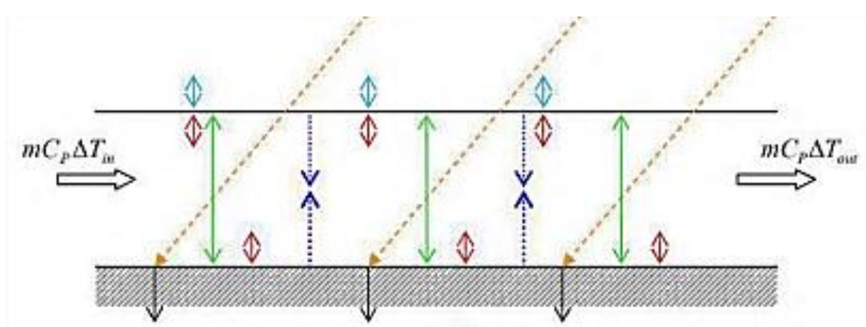
The SCPP is essentially a system with a chimney at the top that creates the draft, a large solar collector at the bottom that absorbs solar energy, and a power conversion unit (turbine and generator).

2.1.1 Component of solar chimney power plant

The chimney is a pressure tube that creates the pressure difference between the ambient air at the top of the chimney and the heated air at the bottom. It has acceptable friction loss due to its low surface area to volume ratio [1] [2]. The suction formed by the plant's updraft tower draws ambient air into the collector, improving the buoyancy of the hot air in the system. According to research, the rise in collector air temperature and the height of the solar chimney is inversely related to the mass flow of the updraft air [6]. In this brief review discussed, to generate a large amount of power, the system needs to be on a large scale. If such systems are to create considerable amounts of power, they must be quite large, Due to this, numerous researchers have chosen the numerical approach, particularly CFD methods, in their investigations due to the high expense of solar chimney construction [7].

Collector

The heat exchanger of the power plant where solar radiation is received and converted into thermal energy is the solar air collector of a SCPP. when the absorbed heat in the collector is transmitted to the air in the greenhouse, it is converted to kinetic energy. A support matrix, column structure, transparent roof, and ground are all part of the solar air collector [2].



Incident solar radiation   Natural convection with ambient air

Forced convection

Radiative exchange (cover and ground)

Natural convection

conduction the ground

Figure 2.1 Collector heat transfer and thermal balance scheme [1]

As shown in figure 2.1 the temperature gradient causes the air under the collector in the system to flow upward in the central chimney as a result of the heating process occurring in the collector. Due to the buoyant force and the conventional effect, these effects cause the air to accelerate upward. In order to facilitate the upward movement of this air, solar chimney, power plants' collectors are designed to rise from the entrance to the collector outlet. The collector height is therefore higher near the chimney entry.

Energy storage

Utilizing thermal storage has a significant impact on improving the efficiency of solar chimney power plants. for the ongoing production of power, including at night. Sand gravel and the black tube under the collector that is filled with water are the two most popular heat storing methods.

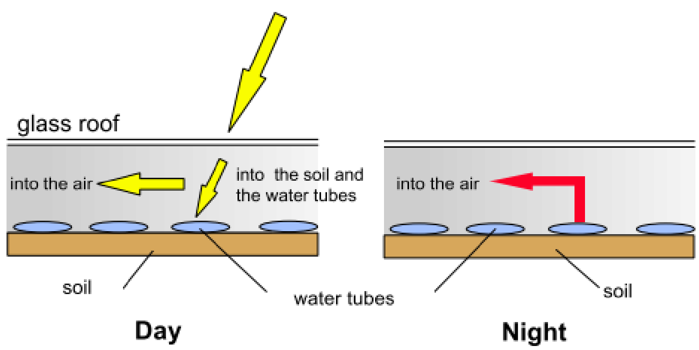


Figure 2.2 Principle of heat storage underneath the roof using water-filled black tubes [3]

Because water has a much higher heat capacity than soil (0.75 to 0.85 kJ/kg) and because the heat transfer between water and black tubes is much greater than that between the ground surface and deeper soil layers, a portion of the solar heat is stored in the water inside the tubes and released at night when the air in the collector cools [3].

Power conversion unit

The Power Conversion Unit (PCU) consists of one or more turbines coupled with a generator, one of the key components of a solar chimney power plant is the turbine. The solar collector, the chimney, and the generator are additional systems. Through openings between the pillars supporting the chimney, the air heated by the solar collector encircling it enters it radially. To serve as inlet guiding vanes, the pillars may be airfoil-shaped and organized along non-radial chord lines. The axial flow kind of solar chimney turbine is the most common. It shares traits with both wind turbines and gas turbines: it has more blades than the typical two or three found in wind turbines, but fewer than those found in gas turbines. The rotor blades are adjustable, just like those found in wind turbines, but the flow is enclosed, just like in gas turbines. The solar chimney turbine may also have radial inflow inlet guide vanes. The effective transfer of fluid power to shaft power is the turbine's primary purpose. The ability to manage flow and output power by adjusting the blade angles of solar chimney turbines is one of their secondary uses [8].

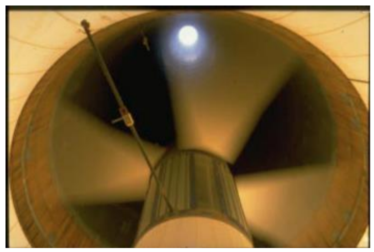
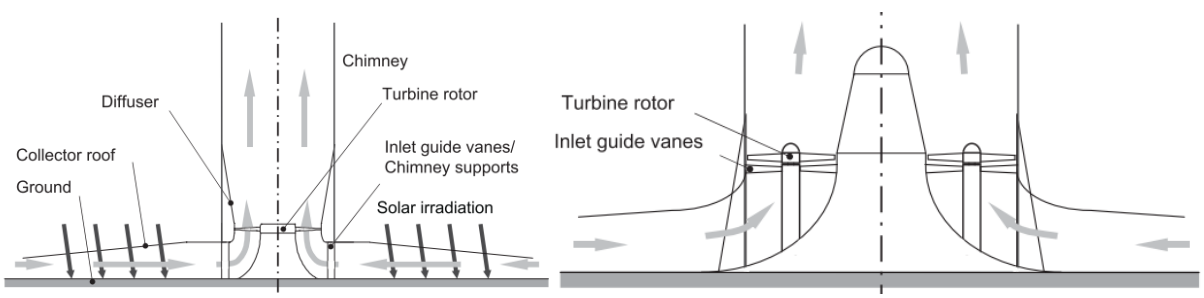
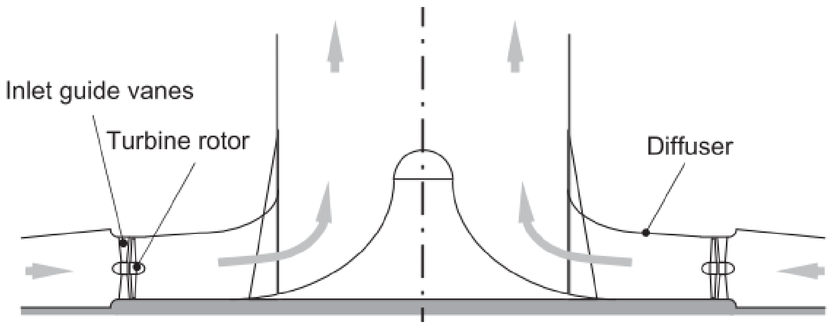


Figure 2.3 Turbine of the Manzanares prototype power plant [8]

Units for solar chimney power conversion have been proposed in a variety of turbine designs and configurations (PCU). As illustrated in figure 2.3 in the Manzanares pilot plant, a single vertical axis turbine without inlet guiding vanes was employed. For a large-scale solar chimney, a similar single vertical axis turbine layout employing the chimney support structure as inlet guide vanes has also been proposed. The use of numerous vertical axis turbine configurations and turbine designs with just one pair of counter-rotating rotors, either with or without inlet guiding vanes, have also been suggested. However, it has recently been proven that an arrangement of numerous horizontal axis turbines and a single rotor layout with inlet guide vanes as shown in figure 2.4 offers the lowest cost of electricity [8].



a. Single vertical axis (VA) turbine b. multiple VA turbines, and



C. multiple horizontal axis (HA) turbine

Figure 2.4 Single vertical axis (VA), multiple VA turbines, and multiple horizontal axis (HA) oriented turbines [9]

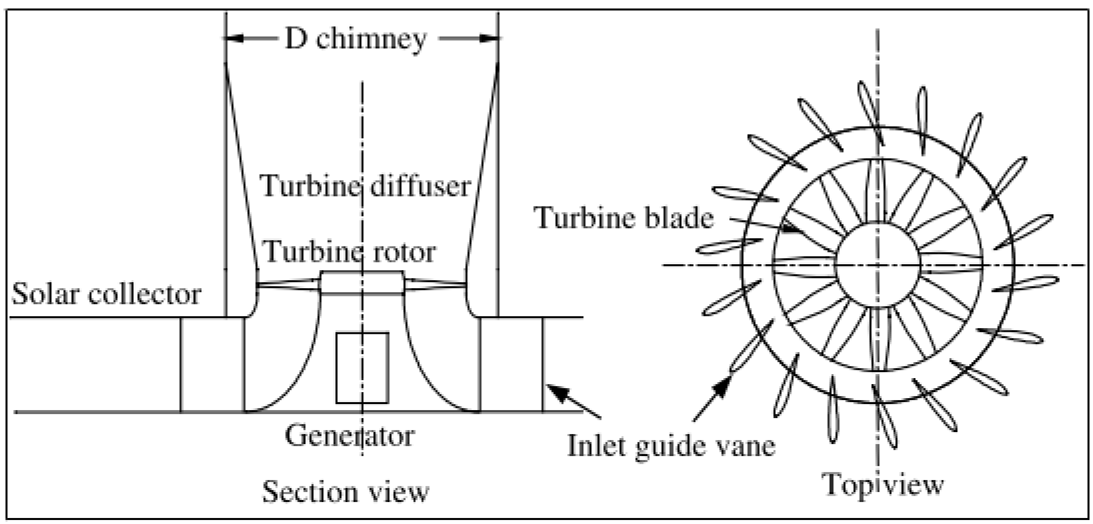


Figure 2.5 Solar chimney turbine layout [10]

the study describes a proposed radial turbine as shown in figure 2.5 that would be installed at the bottom of the Manzanares SCPP, the only sizable prototype ever constructed. The performance of the turbine when installed in the SCPP was evaluated using three-dimensional computational fluid dynamics (CFD) simulations. The maximum power output, which outperformed the original axial turbine used in Manzanares by more than 40 kW, was 77.7 kW at a shaft speed of 15 rpm for a solar radiation of 850 W/m^2 [9].

The SCPP is a design for producing thermal energy with solar assistance and consists of three components: a collector, a chimney made of concrete, steel, and polyvinyl chloride (PVC), and a power conversion unit (PCU) that is a wind turbine generator that converts the heated air in to kinetic energy, which is then converted into electrical energy as shown in Figure 2.6.

The collector is composed of an absorber plate and a transparent cover (collector roof) (base plate). The basic idea involves absorbing solar energy using a sizable absorber plate that is painted black for optimal absorption, warming the chilly air beneath the collector roof. The transparent cover lets sunlight into the collector. By collecting solar radiation, the absorber plate emits radiation into the surrounding air and generates a convective current as a function of buoyancy.

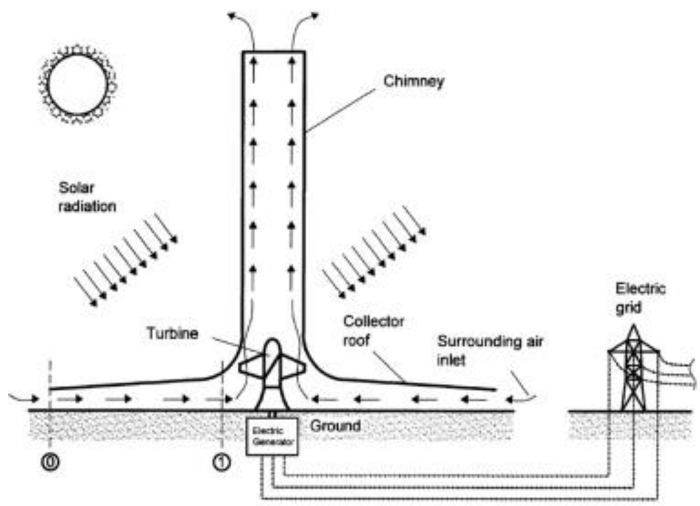


Figure 2.6 Schematic overview of the solar tower principle [11]

The temperature difference between the air within and the air outside causes the chimney to create a negative draught. Fresh ambient air enters the collector to fill the space left by the hot air's passage via the chimney, creating a gap. The void gets heated up and the cycle continues. An attached wind turbine and generator use the kinetic energy of the heated, moving air at the chimney's entrance or the collector's outlet to generate electricity. The wind turbine rotates as a result of the system's constant airflow [12].

2.1.2 Performance enhancement of SCPP

SCPP systems produce clean, environmentally friendly energy, although their drawbacks of poor efficiency and high construction costs have made it difficult for them to be successfully commercialized. Researchers have concentrated on identifying the most efficient new configurations and cutting-edge alternative methods to raise SCPP effectiveness to lessen these issues. Using various techniques, evaluating various setups, and optimizing key parameters.

The review assessed in terms of the unit's overall efficiency and output power. The power output and efficiency of the plant are anticipated using intricate mathematical modeling for a wide range of design and operational parameters relating to the fluid flow and heat transfer characteristics. Beside to that, the performance of solar chimneys is impacted by a number of parameters. It offers new designs while recommending ways to improve the system's performance [13]. In this paper a total of six different baffle types were created, and the corresponding SCPPS models were developed. The Solar Tracking technique was used in numerical simulations to analyze the heat transfer and flow properties of the SCPPS with various baffles. In addition to the experimental verification, it is demonstrated that the system's temperature field, pressure field, velocity field, and power output may all increase to variable degrees with the addition of baffles [14]. In this work two-dimensional steady state numerical Simulation states, the effects of solar radiation, turbine pressure drop, and turbine efficiency are examined in relation to the features of the solar chimney system's flow, heat transfer, energy loss, and power output. Analysis reveals that the effects of solar radiation and pressure drop over the turbine are rather significant. The system's main source of energy loss is the enormous outflow of hot fluid from the chimney outlet, although the canopy loss is also quite significant [15]. The performance of the power plant is affected by modifying the configuration of the components of the power plant: the draft and collector.

2.2 Geometric Configuration of Chimney and Collector

The basic and simplest solution to the low efficiency is to improve the primary components and adjust their fundamental configuration. In compared to interconnecting systems or using several components, this is cheaper and simpler. To increase SCPP effectiveness, many researchers have concentrated on using various setups and optimizing relevant factors [16]. The power plant's various configurations, which range from a to f in Figure 2.7, are as follows:

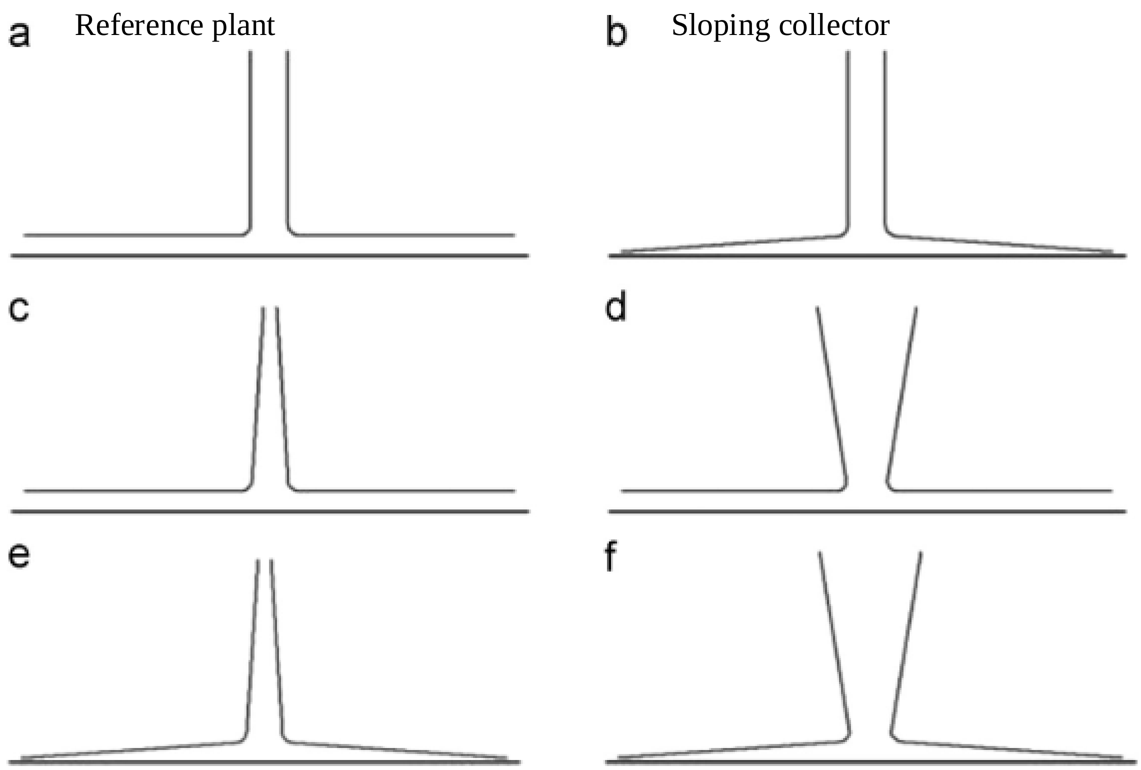


Figure 2.7 Shows various configuration of the schematic layout of the SCPP [17]

2.2.1 Chimney configuration

Research of various chimney configurations, which may involve altering the chimney's cylindrical shape or putting out new arrangements. The efficiency of the chimney and the overall efficiency of the system are both significantly influenced by SCPP's chimney height. According to the literature, an economically feasible SCPP requires a chimney height of at least 1000 meters. However, if the chimney height is lower, an increase in the collector area can serve as a substitute [18]–[22]. Researcher state a computational fluid dynamics (CFD) conducted using the finite volume code, ANSYS Fluent. The model is included Manzanares prototype-based concept. The SCPP's power production rises with chimney height and collector diameter. However, there is a maximum for both collector diameter and chimney height at which the attainable power output rises at a diminishing rate before becoming constant [23].

2.2.2 Divergent chimney

To enable a better understanding of various shape characteristics, the effects of divergent and chimney angle and chimney height were explored. Results were contrasted with a reference case that featured a cylindrical chimney shape. Figure 2.8 presents the schematic of the geometry of divergent and cylindrical chimney. Since the diameter of the divergent kind of chimney rises slightly with height, the low static pressure at the chimney entrance is affected, which significantly impacts the air velocity value and encourages more airflow within the system [24]. Study conducted the performance of the solar chimney power plant affected by chimney shape on the local characteristics. Four chimney designs is used to evaluate the system that are small cylindrical chimney, wide cylindrical, conical, and parabolic chimney are analyzed. And determine the hyperbolic chimney does have the highest performance [5]. suggested a diffuser-type chimney to boost the system's power generation. A focused airflow in the collar enhanced power output and flow speed throughout the chimney, but especially at the bottom, according to the results of CFD research in large-scale plants. This idea was subsequently investigated on an indoor scale solar chimney. They found that a 4° divergence angle enhanced the power output by around three times compared to a straight chimney [25]. Proposed ideal range for chimney height and diameter, however, raising these values was found to improve performance and have the greatest effect on chimney diameter [26].

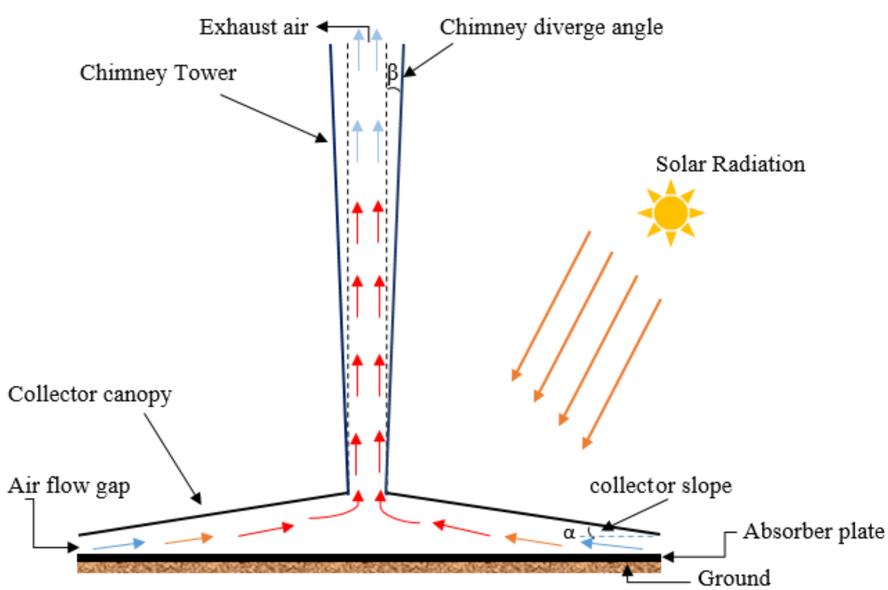


Figure 2.8 Schematics of divergent chimney with sloped collector

Small outlet-to-inlet AR cases have no backflow and the flow increases properly, but bigger outlet-to-inlet AR cases have stall phenomena. Even greater divergence angles cause boundary layer separation to occur deeper down inside the chimney and backflow to occur over a larger section of the flow area. This backflow forces the outside air into the chimney, which lowers the temperature there and significantly lowers buoyancy and pressure potential [27]. In terms of obtaining maximum power performance metrics, AR is crucial. For the reference sample, the mass flow rate of air mass flow rate is found to be 1122.1 kg/s; however, for the AR of 4.1, it is increased to 0.83% [28].

2.2.3 Collector design

There are several specific sorts of collector configurations, but the most common are convergent, divergent, and zero-degree collectors. Dimensions, on the other hand, have a significant impact on the operation of a solar chimney power plant. The impact of the collector roof angle on the solar chimney was studied using convergent, divergent, and zero-degree collector roof angles. This alters the thermal characteristics of the air flow and indicates that the angle of the collector has a significant impact on the overall efficiency of the solar chimney power plant [29].

The study shows effect of Collector Geometry on the performance of Solar Chimneys Regarding the solar chimney, by experimental and numerical analysis the effect of three distinct collector reduction areas was presented. Which shows the performance of the solar chimney is substantially influenced by the collector reduction area. The best performance is achieved with a 1.28 cm collector reduction area [30]. Different geometrical parameters are used to display the temperature, pressure, and mass flow rate profiles. Studies are present in North West part of Libya investigating the performance of a solar chimney by experimental and theoretical evaluation. The experimental result shows the floor of the solar collector stores some thermal energy during the day and releases it during the night; for this reason, using absorbers with high thermal capacity in solar chimney power plants is important to produce electricity after sunset [31]. The other paper presented related to the construction of SCPP, the amount of power produced per square meter of land is related to the power plant's length scale. Thorough mathematical model verifies the analysis. The system's dimensionless length scale is used to report pressure losses [20]. On the other side, this paper determined the performance of the novel SCPP design, a thorough thermodynamic analysis was conducted, and the results were contrasted with those of a traditional SCPP. Using engineering equation solver software, all simulated energy and energy balance equations were simultaneously solved. According to the study, utilizing reflectors to boost incident solar radiation increases the efficiency and power output. The increased mass flow rate is what causes the increase in power output [32].

2.3 Recent Research Finding

Many academics are focusing on optimizing solar chimney power plants by modifying the system components' design characteristics. A mathematical model was developed by undertaking more than three sites. They discovered in this work that there is a maximum electrical power with a collector efficiency less than 100% and a minimum flow rate. While the collector efficiency is at its peak of 100%, the output power is somewhere in the middle. The power output altered with the design parameters. In spite of that, the study found that when the power output exceeds 100 kW, the optimum dimension of collector diameter and chimney heat is more than 200m and 170m consecutively [39].

Geometrical optimization is necessary for quality power generation. According to the findings of this study, when the chimney height climbed from 100m to 400m, the power generation efficiency increased linearly from 0.08% to 0.37% [40]. Chimney height directly related to the chimney efficiency. In Manzanares, the efficiency of the chimney was 0.1%, and also the study showed that when the chimney height increased to 200 m, the efficiency of the chimney raised by 0.65%. In addition, utilizing sand as thermal storage increases energy production by 35% when compared to a power plant without storage [41]. In addition, in this study, the chimney height and efficiency increased exponentially. Although when the chimney radius increase, the efficiency decrease by 28% [42].

To reduce the construction cost, determining the optimum height is the key. A study found by taking different small-scale chimney height from 0.1m to 2 m, the optimum chimney height was 1.5m [43]. On the other hand, a research was done to compare the conventional Manzanares power plant with the diverging chimney in order to reduce the chimney height. The conventional chimney's 50 kW power output at 194.6m height can be obtained at 20% of its height in a divergent chimney. According to the research, divergent chimneys achieve 42.14 times the power of a traditional power plant at the same chimney height [44].

Another research was conducted to optimize the power plant and improve its performance. The chimney and collector's dimensional matching was evaluated. According to the study, the best chimney radius for maximum power was 200 m [45]. The geometry of the chimney and the collector effect are studied numerically. Different chimney configurations were investigated, with heights ranging from 1.5 m to 3.5 m. The diameter of the chimney at the entrance is 0.25 m, with the collector radius ranging from 0.1m to 1.5m. Among the various configurations, the diverging chimney achieved 0.54 W, which is greater than the other configurations. According to the research, increasing the height of the chimney increases the system's power production. Although increasing the collector radius has a substantial impact on improving air velocity, temperature, and plant power output. However, the increase in collector diameter on the power output is restricted to 4 m; beyond that point, the power decreases [46].

The study investigated the effect of changing the height of the chimney on the air flow properties. When the chimney height ranged from 3 to 8 meters, the velocity of air at the chimney base will increase from 1.617 m/s to 2.338 m/s. Although when the collector inclination angle increases from 25° to 30°, the power output declined from 0.38W to 0.11W. This happens due to the decreasing of pressure drop. In spite of that, the maximum power output was achieved with H_{ch} = 7m, θ_{coll} = 30°, D_{coll} = 5 m, and D_{ch} = 0.6m. In this specification, the output power shows an increment of 60.4% compared to the generalized. As a result, the study estimates that the theoretical power output will increase by 93%, along with the overall efficiency of the system by 86.6% [47].

In this paper, the effect of different diverging angle of chimneys (β = 0°, 3°, 6°, and 9°) on velocity and temperature was investigated. The velocity of the air flow has a considerable impact on the power plant. The diverging angle of the chimney influences the velocity increment or decrement, for this reason the highest velocity was obtained at 3°. The reason for this is that when the angle becomes higher, backflow occurs, causing a stall due to the eddy effect. Temperature, on the other hand, has a negligible effect on the change in chimney divergence angle [48]. Likewise, a study was conducted on the chimney divergence angle ranging from 1° to 5°. Moreover, demonstrated that the influence of divergence angle on the system performance. According to the numerical analysis based on the performance parameters affecting the system, the 2° chimney angle is the best for optimal performance. At 1°, the calculated velocity was 3.22 m/s, with a maximum velocity of 3.53 m/s at 2° [49].

A study conducted on the performance of a diverging chimney to demonstrate the effect of the chimney's coefficient of area ratio on the flow parameters. It evaluates using the Manzanares power plant as a point of reference. The main focus is on how the backflow and stall formed in the chimney and affect the power output. To demonstrate, different chimney outlet to inlet area ratios

(COAR) of 8.7, 11.9, 15.5, and 24.2 are used. At COAR = 8.7, the air flows uniformly with no stalling or backflow, whereas at COAR > 8.7, stalling, backflow, and vortices are created, resulting in a decrease in power plant performance. Aside from that, increasing the total pressure potential improves the plant's performance. In light of this, they proposed that a low coefficient of area ratio can increase the power output of a solar chimney power plant [36].

The paper evaluated the performance of a solar chimney power plant using 3D computational fluid dynamics (CFD). The geometric characteristics of the Manzanares power plant were employed in the analysis. They also compare the outcome to that of the experimental prototype. The simulation is based on solar radiation at 1000W/m^2 and an ambient temperature of 293.15K. It was discovered that when the mean temperature rises, so does the power production. Regardless, the power output increases when the ambient temperature decreases, but the power output decreases in the opposite direction. As a result, the maximum power of 49.663 kW was attained at 293.15 K, while it was 8.389 kW lower at 320 K. Moreover, they used Sandstone as a thermal storage in the simulation to increase the power output by increasing the mean temperature [50].

A study was carried out on the integration of the bell mouth on the collector inlet and divergent chimney. When compared to a traditional chimney power plant, the use of a bell mouth on the power plant increases the flow velocity by 6% to 7%. As a result, the turbine power output increased by 21%. In addition, they examined 90^o upward, 90^o downward, and horizontal bell-mouth configurations. The result demonstrates that the upward and downward 90^o of the bell-mouth show continuous flow velocity, but the horizontal displays variability. It represents that in a traditional power plant, the velocity at the inlet of the chimney is high, whereas in the case of a bell-mouth flow, the flow is continuous. Furthermore, they combine the best chimney design with bell-mouth integration, with the highest velocity reached at the optimal coefficient of radius ratio (CORR) = 2. This increase the system's velocity by 270% over that of a typical solar chimney power plant. As a result, the collector area can be reduced by 7 times and the chimney height by 40%. They proposed by incorporating a bell mouth into the collector intake, the power output of the Manzanares power plant can be boosted from 50 kW to 1738 kW [51].

The influence of chimney height and divergence angle on collector slope variation was investigated in this study. Based on the geometrical parameters of H_{ch} = 180 m-210 m, chimney divergence angle (β) = 2^o, 4^o, 6^o, and collector slop (α) = 2^o, 4^o, 6^o, 8^o and 10^o, the simulated result is presented. When the chimney height increases, the velocity and power output rise as well. The convergent collector, on the other hand, improves the heat transfer inside the collector and the suction effect of the chimney. Although 6^{o} is the optimal collector slope angle, any above that causes recirculation of air to the collector. In the instance of chimney diverging angle, they indicate that the optimum angle is 2^{o}, the flow remains uniform, and the power increases by 107.7% compared to zero chimney diverging angle. However, a greater divergence angle causes a decline in velocity and, as a result, a stall will occur [35].

Modifying the geometry of the collector, which modifies the airflow that passes through the chimney, is also essential. One method for improving the performance of a solar chimney power plant. The study looked at how different concavity ratios affected air flow velocity and system power production. A velocity of 2.5 m/s was obtained with a concavity ratio of 0.3, which is greater than the zero concavity ratio. As a result, the theoretical power output increased by 112% [52]. Some researchers take a unique method to improve the performance of solar chimney power plants. for those who use nuclear waste heat to create power at night and improve overall efficiency. According to the study, employing nuclear power plant waste heat increases the power output of Manzanares SCPP by up to 150% annually [53].

The effect of a diverging chimney on the theoretical power output was studied experimentally. They investigated three divergent and three cylindrical chimney models developed in the laboratory with heights of 1 m, 1.5 m, and 2 m. The collector is constant in all cases at 0.8 m^2. Aside from that, the velocity is high in the shortest chimneys due to no loss and a tiny cross-sectional area. Furthermore, at 1 m, the velocity of the divergent and cylindrical chimneys is 0.994 m/s and 0.820 m/s, respectively. They also investigate the influence of mass flow on the cylindrical and divergent chimney heights. It indicates an increase in both situations due to the rise in cross-sectional area. At a 2 kW electric heat load, the 2 m divergent chimney produces 0.183 W. The maximal theoretical power was attained at 2 m in both cases, however. The power increment of the cylindrical chimney was 11% from 1 and 1.5 m, but the power increment of the divergent chimney is 37.15% [54].

A review of experimental studies was carried out according to the report. So far, 20% of the papers reviewed on solar chimney power plants have been experimental work, Table 2.1. To improve SCPP performance, system component optimization, hybridization with geothermal waste heat, nuclear waste heat, and integration with photovoltaic cells (PV) are considered. They also examined the power plant's environmental sustainability [55].

Table 2.1 recent review paper summery

Author	Description	Type
Attai, 2021 [39]	The influence of the chimney's configuration and dimensions on the power output of the power plant is explored. The influence of mass flow rate, pressure drop, temperature, and velocity was determined.	Mathematical
Li, Guo and Huang, 2016 [40]	The quality of energy conversion and transmission was investigated. Using a comprehensive mechanism model and a streamlined unsteady mechanism model. As well as the relationship between geometric parameters and power output.	Numerical
Attig-bahar *et al.*, 2019 [41]	the influence of thermal storage on SCPP performance. that ratio of released to stored energy is primarily determined by the season and energy production. When compared to a system without storage, it grew by around 35%.	Numerical
Toghraie *et al.*, 2018 [42]	The effects of geometrical characteristics on a solar chimney performance are being investigated. The impacts of variables on temperature, velocity, pressure, efficiency, and output power are presented.	Numerical
Bansod, 2020 [43]	The influence of chimney height on the velocity, temperature, mass flow rate, and power output studied. Moreover determining the optimum height of the small prototype.	Experimental
Pratap *et al.*, 2023 [44]	investigate the height decrease of a high performing diverging chimney with the same power output of the long cylindrical chimney. Based on price and performance.	Numerical
Cottam *et al* [45]	Match the dimensions of the main components of the chimney power plant. as well as determine the optimal dimensions of the collector and chimney.	Numerical
Ayli and Nsaif, 2020 [46]	analysis to the performance optimization methods and determining the ideal configuration of a SCPP model. The influence of chimney height and collector radius	Numerical

	on the power output and efficiency of the system, considering material and construction cost.	
Das and Chandramohan, 2019 [47]	The influence of chimney height, collector roof angle, and absorber plate diameter is investigated. The increase in chimney height from 3 to 8m increases the velocity by 40%.	Numerical
Nasraoui, Driss, Ayadi, *et al.*, 2019 [48]	the influence of collector concavity on power plant performance by altering the collector's concavity ratio. The airflow behavior within the collector was investigated by examining the static temperature, magnitude velocity, static pressure, and overall percentage of power output rise.	Experimental and Numerical
Das and Chandramohan, 2021 [49]	The effect of a divergent angle chimney on the flow and performance of a solar updraft tower (SUT) plant. The optimal divergence angle was found to be 2º.	Numerical
Xu and Zhou, 2018 [36]	Varying the coefficient of area ration (COAR) of the chimney to evaluate its performance. The ideal COAR was discovered to be 8.7.	Numerical
Cuce, Cuce and Sen, 2020 [50]	The assessment of performance is based on changes in solar radiation and ambient temperature.	Numerical
Singh *et al.*, 2021 [51]	To increase power output, a bell mouth was integrated on the entrance of the converging diverging solar chimney power plant.	Numerical
Ahirwar and Sharma, 2019 [35]	Investigate the effect of a solar chimney power plant by varying the collector slope, divergence angle, and chimney height.	Numerical
Fathi *et al.*, 2018 [53]	Using nuclear waste heat to improve the efficiency and performance of solar chimney power plants.	Numerical
Jawad *et al.*, 2021 [54]	The effect of a diverging chimney on the theoretical power output was investigated in a laboratory-controlled experiment. The performance of three small-scale chimney heights and divergence angles is examined.	Experimental

2.4 Comparison of Solar Chimney Power Plants

The geometrical structure of the chimney, from which the chimney diameter is primarily derived, serves as the comparative parameter for the solar chimney power plant. There are three basic parts that make up a power plant: the turbine, the collector, and the chimney. Despite the fact that the chimney design is the main subject of this review.

In contrast to divergent and convergent chimneys, which have different inlet and outlet diameters and divergent angles, the design of a cylindrical chimney has a constant diameter throughout the height. Research indicates that the solar chimney's 2° diverging angle (DA) is suggested for the solar chimney power plant design, ensuring that the system operates to its fullest potential.

The power plant's operating concept is the same regardless of the various chimney layouts. The size and shape of the chimney have a big impact on the plant's output of power. Although, in the case of divergent and convergent chimneys, the diameter of the chimney has a major impact on the system's power production. Comparatively speaking with other chimney designs, the effect is reduced with cylindrical chimneys. In a convergent tower, the top velocity increases while the mass flow rate drops, resulting in a kinetic energy that is comparable to that of a tower with a constant area. While in a diverging tower design the maximum kinetic energy and velocity are both located at the base of the chimney, respectively, the velocity increases near the base of the chimney. Regarding to this, the study compares cylindrical and different size divergent chimneys using modeling and experiment. The result shows the effectiveness of the chimney rising as the divergence radius increased. It has been highlighted that the stated designs' efficiency is higher than a typical SCPP when compared to the particular design and the regular solar chimney [33]. On the other hand, it is investigated how various chimney layouts affect power output and efficiency. The outcome depends on the air velocity, pressure drop, and efficiency of the turbine. Conical chimneys are not advised due to their lower power output and higher pressure drop, which impair the air flow velocity. Moreover, due to the high cost of construction and failure to maintain the required pressure drop for maximum power output. As a result, for obtaining the maximum power output and efficiency, the cylindrical chimney is preferable to utilize from the other configurations since it has the lowest flow resistance and the highest mass flow rate [34].

Table 2.2 Power output of different divergent SCPP

Author	method	Diverging angle (β)	Chimney height (m)	Collector diameter (m)	Power output (kW)
(Ahirwar and Sharma, 2019) [35]	Numerical	2º,4º,6º, and 8º	180, to 205	244	47.12 to 38.38
(Xu and Zhou, 2018) [36]	Numerical	0º, 2º, and 3º	195	200,220,240,and 320	80 to 144
(Nasraoui, Driss, Ayadi, et al., 2019a) [37]	Numerical	0º, 3º, 6º, 9º	2.95	3.7	0.2 to 0.25 W
(Cuce et al., no date) [28]	Numerical	Aria ratio: 0.5 to 10	194.6	244	168.5 at optimal 4.1(AR)
(Kebabsa, Said Lounici and Daimallah, 2021) [38]	Numerical	Aria ratio: 0.25, 0.5, 0.75	1.7	240	41 to 44

2.5 Research Gap

Many theoretical, experimental, and numerical studies on SCPP have been conducted over the years as a result of several literature reviews, and extensive research has enabled many drawbacks to be overcome. However, the system has yet to be commercialized due to its low conversion efficiency. To address this, various measures are being implemented, primarily by increasing the chimney height, changing the geometrical dimensions of the main component, and determining the optimum value for the main performance-affected parameters. Despite the fact that only one practical prototype has been developed to date, the research shows the way to increase the power output of the SCPP through geometrical configurations, such as changing the chimney's cylindrical shape to divergent and convergent as well as the collector shape to enhance the power output. Although most studies are limited to CFD analysis, some are laboratory-controlled experimental investigations. Hence, in the research, there is limited experimental investigation to analyze the performance of the divergent and cylindrical chimney power plants performance compared to the numerical analysis. Therefore, in this paper the experimental investigation of cylindrical and divergent chimney will address.

CHAPTER THREE

3 METHODOLOGY

To conduct the research, experimental methodological approaches are used. Using this technique, the capacity of divergent and cylindrical chimney power plants was compared. The experiment takes place at the Addis Ababa Institute of Technology. Data is acquired using a measuring device, and the obtained data is analyzed using a mathematical equation. to compare the two models and determine which design and configuration have better performance.

3.1 Assumptions in Design of Solar Chimney Power Plant

The assumptions to be considered to prepare the prototype of SCPP

- ✓ The component of the SCPP selected based on the availability of the material on the local market with convent efficiency
- ✓ Cost of the material also considered
- ✓ Consider the solar chimney material has no loses or insulated.
- ✓ Non uniform heating of the collector surface in terms of the suns altitude angle is neglected.
- ✓ The collector placed on horizontal surface.
- ✓ The heat radiated to the chimney is ignored since the collector's surface area is substantially larger than the surface area of the chimney. Because the temperature difference across the chimney is modest, the heat transfer equation is only considered for the collector, and the collector inlet equals the chimney exit.
- ✓ Previous study defined the turbine efficiency for this power plant as 80%. It is assumed that the process across the turbine is reversible and adiabatic.
- ✓ Heat transfer from the system to the surrounding environment was neglected, and only heat transfer from the surrounding environment to the collector was addressed.
- ✓ Across the chimney, the flow is incompressible. As a result of the heat generated inside the collector, the density of the air decreases, causing a natural flow towards the chimney propelled by buoyancy force.
- ✓ In the equation, the uniform solar heat flow average over the day period is used. Determining initial design parameter.

Table 3.1 Parameters determine the performance of power plant

Case	Inlet D_{ch}, (m)	H_{ch}, (m)	D_{coll}, (m)	α (collector angle)	β (divergent angle)
1	160	250	2.0	6^o	2^o
2	160	150	2.0	6^o	2^o
3	160	350	2.0	6^o	2^o

3.2 Prototype Development

3.2.1 SCPP configuration

The plant's performance and ability to produce power are significantly impacted by chimney height (H_{ch}) and diameter of the collector (D_{coll}). The primary factor affecting the SCPP's geometrical Table 3.2dimensions is its H_{ch}/D_{coll} ratio. Previous studies have shown that the ideal range for the chimney height to collector diameter is between 0.8 and 5 [31], [57]. For this study solar chimney prototypes, the same ratio of collector diameter to chimney height is used. However, the diameter of the chimney was different for the two prototypes. This was based on what was readily available in the local market.

Based on this, the divergent chimney was constructed using a 2.50-meter-hight rolled galvanized sheet metal, which was selected for the reason of its ease of fabrication, corrosion resistance, and high strength while the cylindrical chimney was constructed using a polyvinyl chloride (PVC) pipe. PVC pipe was chosen because of its characteristics of lightweight, easily available and high resistivity to atmospheric temperature conditions for small-scale SCPP. The entrance and outlet diameters of a diverging chimney is 0.16 m and 0.346 m, respectively. Whereas the diameter of the cylindrical chimney is 0.16 m throughout its height. The output of the generated power is significantly influenced by the chimney's shape [37]. To ensure that the system operates to its greatest capacity, the 2^o divergent angle (DA) of the solar chimney is chosen for any sized arrangement of solar updraft tower (SUT) plant design [49].

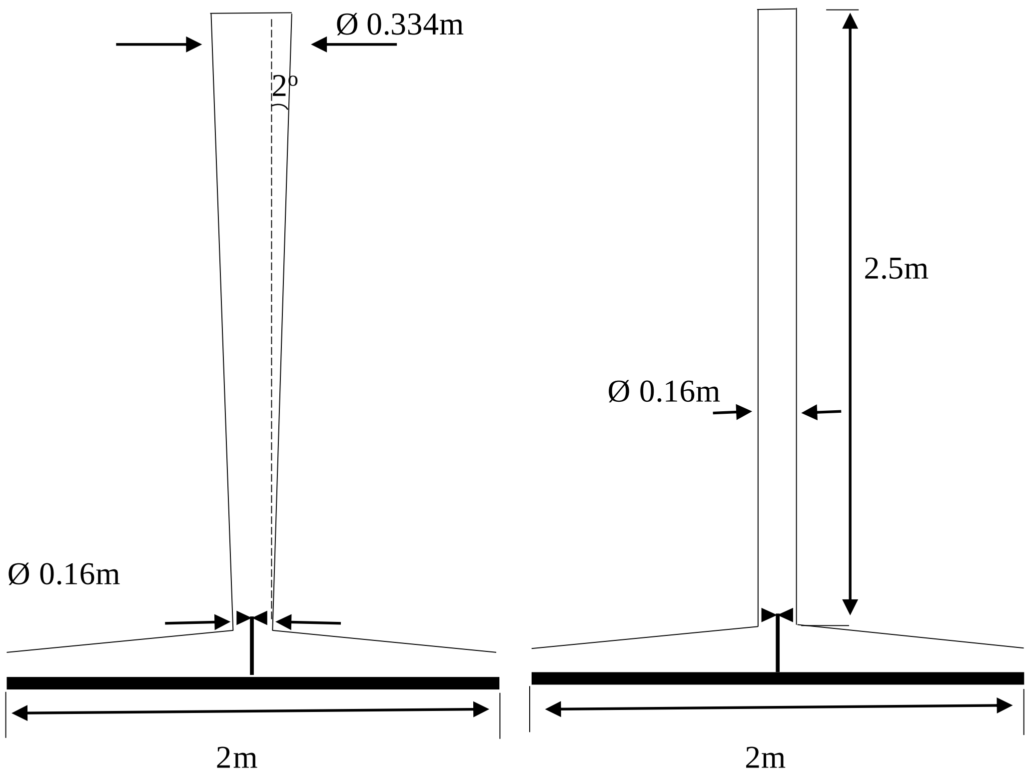
The collector has a conical, circular shape and is covered with an absorber plate below a polyethylene canopy that is transparent. Because inclined collectors can capture more solar energy than flat collectors, which improves heat transfer, the temperature can rise as the collector slope increases thanks to the conical shape of the collector. Additionally, an uneven distribution of temperature is caused by the angle of the collector, which causes some areas to receive more solar energy than others [58]. Therefore, this study used a sloped collector type with a 2 m collector diameter (D_{coll}) in order to achieve high performance. For the absorber a scrap of black rubber was used because it has a high absorption capacity and it is widely available.

It is necessary to define the dimensions of the cylindrical and Divergent chimney configuration parameters to compare the performance of the power plants. Thus, the dimensions of every component are shown in Table 3.1.

Table 3.3.3 Geometrical specification of SCPP prototypes

Parameters	Indentation	Size
Chimney height	H_{ch}	2.50 m
Cylindrical Chimney diameter	D_{ch}	0.16 m
Divergent chimney inlet diameter	D_{in}	0.16 m
Divergent chimney outlet diameter	D_{outlet}	0.334m
Chimney divergent angle	β	2º
Collector diameter	D_c	2 m
Collector height	h_c	0.1 m
Collector inclination angle	α	6º

There are two SCPP models in this study, each with a distinct chimney structure. The cylindrical solar chimney power plant (CSCPP) has a chimney height of 2.50 m from the collector outlet, a chimney diameter of 160 m, and a collector diameter of 2m. The divergent solar chimney power plant (DSCPP) has the same chimney height as the cylindrical power plant. But the diameter of the chimney at the inlet and the exit is different; 0.16m and 0.334m respectively due to the 2º diverging angle. Furthermore, the collector dimensions are the same for both power plants.



a. Divergent Chimney b. Cylindrical chimney

Figure 3.1 Schematics of solar chimney power plant

3.2.2 SCPP Fabrication

This test will consist of two major components. They are as follows: the collector (transparent plastic cover and black rubber absorber), the chimney, and the turbine. On the ground surface beneath the collector, there is sand on top of it covered by black rubber, which absorbs the greatest solar radiation energy. The solar collector, the tower or chimney, and the turbine are the three main components of a solar updraft tower.

Collector

The canopy is placed on top of the absorber, and thermal energy is stored by reducing the collector's inlet gap to 0.1 m. A frame is constructed to hold the collection cover (transparent plastic). The frame was built from flat bar steel. In the canopy, polyethylene was utilized to receive both direct and diffuse sun energy. The collecting surface gradually increases in proximity to the tower, directing warm air towards it, and then curves steeply up at the tower's foot, transitioning the airflow up the tower. In this study, the collector's base diameter is 2 meters. And has a conical shape structure. The convergent collector stands 0.097 meters high, bringing the total height to

0.197meter including the leg. The ground surface is covered with black rubber. The reason black absorbers are used is because of more heat absorbed than other colors.

The initial stage of the collector steel structure frame. the rolled 30x20mm RHS in 2m withstand leg and four chimney load distributors with two supporting diagonals for stable and centered chimney position. As shown in Figure 3.4 collector is still structured with the circular machined chimney set hole or collector output with chimney support. A flat bar of 20mm x 2mm plastic cover structure is used to stretch the polyethylene plastic and to collect solar radiation effectively. The collector roof is covered with polyethylene plastic due to its high transmissivity, flexibility, and ease of availability in the local market. Also, glue was used to stick the glazing cover to the steel structure.

Figure 3.2 Collector with chimney support

Chimney

The chimney, or tower, is the solar updraft tower's main component. The heated air is sent from the collector into the chimney, where the pressure differential caused by the buoyancy difference between the heated air and atmospheric air allows the air to be propelled up the chimney. Two experimental models one with a diverging chimney and the other with a cylindrical chimney are present in this configuration. Regardless of the chimney diameter or divergence angle, the setup's dimensions are comparable. The galvanized sheet metal that has been rolled into a conical shape with the specified diameter is used to construct the diverging chimney. It was made of three 0.8267-metre-high parts that were riveted together to form a 2.5-metre-high diverging chimney. To maintain smooth flow and link the chimney and collector, a 200-mm support was created. The output of the collector was joined by welding the rolled chimney support, which was tapered to meet the outer diameter of the chimney. The other, a cylinder-shaped PVC chimney that was purchased at the local market, was the same height as the divergent one and 0.16 m in diameter. The physical image of the SCPP's height and other specific geometry are shown in Figures 3.4 a and b.

.

a) Divergent Chimney b) Cylindrical chimney

Figure 3.3 divergent and cylindrical chimney

Turbine

The Turbine of the power plant was installed and the chimney entrance. In this study, an axial flow turbine was used with bearing and housing to connect with the shaft. As seen in the image of the turbine mounted on the chimney bottom in Figure 3.5 below.

Figure 3.3.4 Turbine installation at the bottom of chimney

A variety of materials can be used to construct the chimney and collector. The materials utilized include glass, polyethylene, polycarbonate, polyvinyl chloride (PVC), and polyvinyl fluoride (PVF), at least in part. So that Price, durability, and transmissivity were the main selection criteria [59]. The selection criteria took cost, durability, and transmissivity into consideration. Based on these testing parameters, polyethylene with a transmissivity of 0.85 was selected for the collector cover. And, PVC with a thermal conductivity of 1.185 W/mK, for cylindrical chimney was determined. Additionally, a scrap of black rubber is employed as the absorber because it is versatile and easily accessible. Also, it offers great thermal characteristics, with an emissivity of radiation 0.95 and an absorptivity of 0.92.

3.3 Instruments used for the Experiment

The experiment was carried out to investigate the power plant's main parameters. It was done and recorded for three sunny days; the temperature distribution throughout the system, the velocity of air in the collector inlet, and were all measured at 5-minute time intervals. The main instruments used in the experiment to take the required measurements are listed below in Figure 3.9:

a. Pyranometer b. Anemometer c. Thermocouple d. Data logger

Figure 3.5 Instrumentation

b. Pyranometer

c. The CM3 pyranometer is used to measure the instantaneous sun irradiation during the time of the experiment in five-minute intervals, and data from a data logger is used. The gadget measures a range of 0–1500 W/m2 and has an anticipated accuracy of ±10% for daily summing [60].

d. Anemometer

An anemometer is a tool for measuring the air flow and ambient temperature of the experimental place and the type of anemometer used in particular, to measure the wind speed. At the collector inlet, the air velocity was measured. model type of anemometer used with 0.03 velocity accuracy.

e. Thermocouple

The system's internal temperature was measured using the six thermocouple sensors. The K-type thermocouple is used to measure the temperature in the collector. There are six thermocouple sensors in use: three on the divergent collector and three on the cylindrical. The collector entrance is in the first position, the absorber is in the second, and the collector exit is in the last position. The thermocouple sensor was linked to the data recorder such that it could read the observed value with an accuracy of 0.12%.

f. Data Logger

National instrument NI cDAQ-1972 model data logger is also used to acquire temperature information and solar radiation. By attaching a laptop to it while collecting data Every five minutes, the data is recorded. to make it possible to regularly store data and see it later on a computer. The data logger was utilized at the experimental site to obtain precise data collection.

3.4 Experimental Procedure

An experimental evaluation of the study was done by identifying the factors that affected SCPP performance and reducing the variables. The steps are: gathering the experiment's recorded data, rejecting the data that appeared irrelevant, and finally revealing the outcome. The position of the thermocouple sensor on the collector and the Anemometer (air velocity measurement) position on the collector inlet is indicated in Figure 3.6 along with a demonstration of the sensor point location.

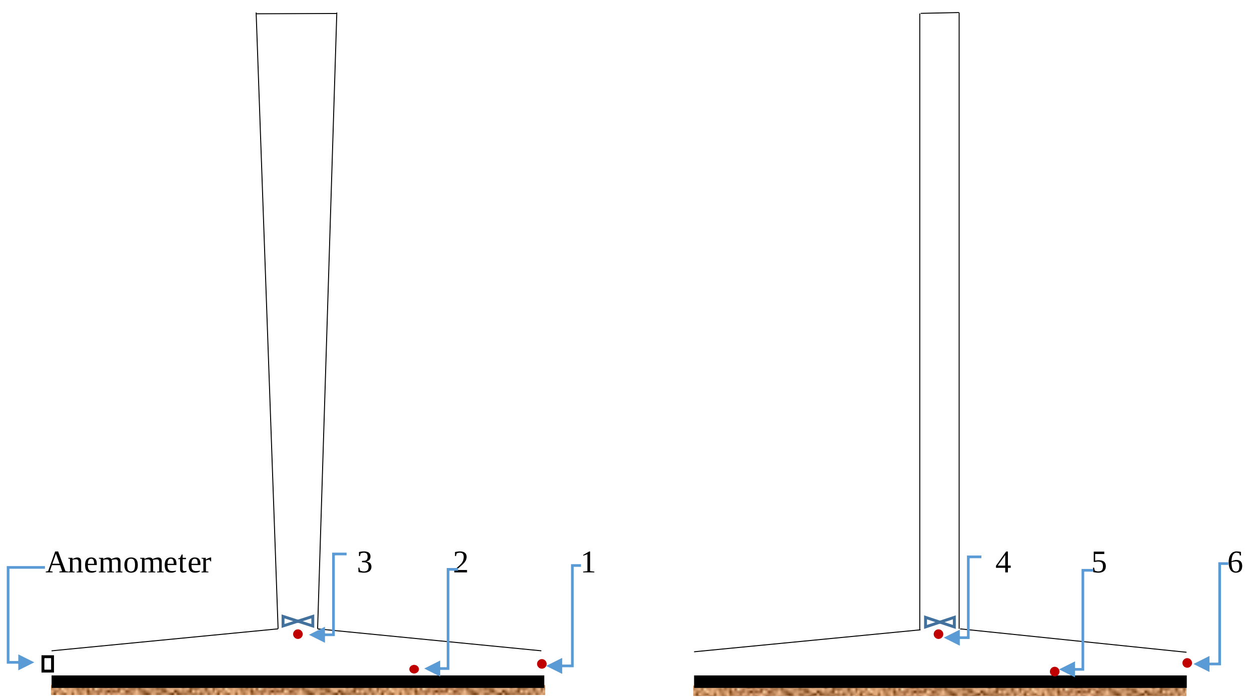


Figure 3.6 Schematics of sensor position

There are temperature sensors fitted into the collector. All of the sensors are positioned on one side, all of which are spaced 0.34 m apart. The ambient temperature is measured at points 1 and 6, which are situated at the collector's entry; points 2 and 5, which measure the heated absorber; and points 3 and 4, which are situated close to the turbine or collector's outlet and measure the heated air exiting the collector. Three temperature sensors are positioned next to one another. Sensors 1, 2, and 3 are used on the cylindrical chimney, whereas sensors 4, 5, and 6 are used on the cylindrical chimney. To measure the air velocity or wind speed, an anemometer is positioned at the collector entrance. The actual experimental setup of SCPP at the time of data collection takes place shown in Figure 3.7. The experiment yielded three different types of data: that are air velocity, solar radiation, and collector temperature.

Figure 3.7 Actual experimental setup of the two prototype

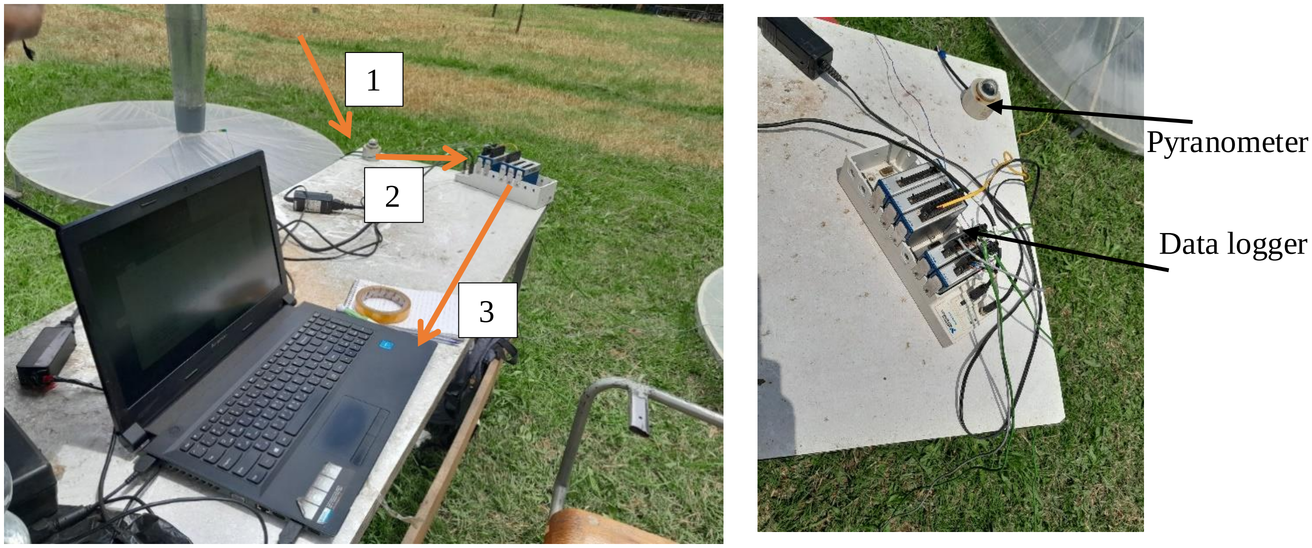


Figure 3.8 Data acquisition process on the experimental place

Combined with the instrument-displayed data acquisition method, Figure 3.8 illustrates how the data was collected at the experimental site. For the experimental inquiry to yield results that are compelling, the following steps must be organized in chronological order, step by step:

- Identify the test location: the location of the experimental work held in Addis Ababa University Institute of Technology (9.04 N,38.7 E). The power plants were faced in the direction of east west orientation.
- Data collection: measurements of the sun's global radiation were made at the experimental location. Additionally, temperature readings for both cylindrical and divergent chimney power plants are made at the collector using temperature sensors. The air velocity observed at the collector's entry needs to be recorded in addition to the other data. Air velocity is monitored at the collector's entry to compare the velocities of the two differently shaped chimneys. Temperature measurements are collected at three locations: the collector entrance, the absorber, and the collector's outlet. Over the course of three days, measurements were made every five minutes.
- Examine the collected data: following data collection, analysis will be conducted to compare the performance of the power plants. At the time of analysis, removing data that didn't seem essential in order to produce a concise and useful result before presenting the findings.

3.5 Data Analysis

There are three kinds of data taken from the experiment those are; temperature on the collector, air velocity, and solar radiation. For the comparison of the power plants. Figure 3.9 shows the location of the main parameter.

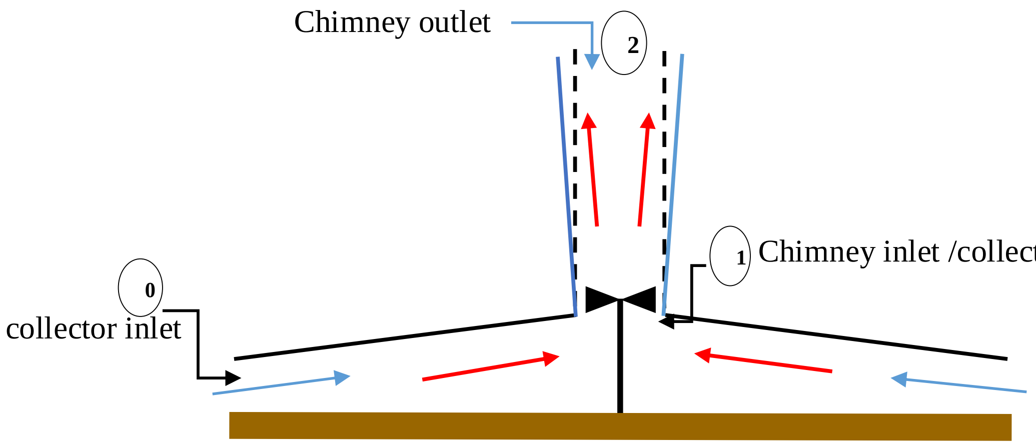


Figure 3.9 Schematic diagram of parameters location

3.5.1 Heat input and useful heat

Equations are used to analyze the data taken on three points at the collector's input, middle and exit of the collector to determine the airflow. Therefore, the mathematical formulas used to determine the mass flow rate, internal energy and global solar insulation on the collector surface; As shown below:

Solar insolation on the collector is given by Equation (3.1) [61],

$$\mathbf{Q_s} = \boldsymbol{GA}_{\mathbf{coll}} \tag{3.1}$$

The energy equation throughout the collector as presented in figure 3.10 can be used to determine the temperature change over the collector [62].

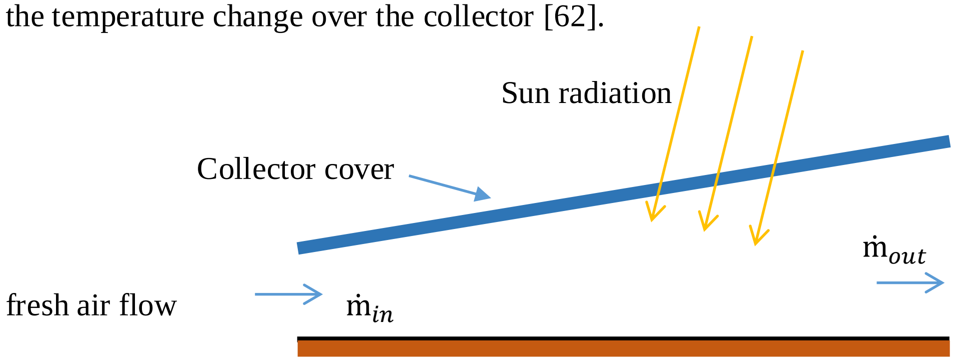


Figure 3.10 collector energy balance schematic

The equation (3.4-2) are used to calculate the mass flow rate of air and the temperature. The difference between the ambient and collector outlet: (T_0) is considered as ambient temperature and T_1 collector outlet. The heat generated $\dot{Q}$ calculated by equation 3.2 and mass flow $\dot{m}$ could be evaluated in equation 3.3;

$$\dot{Q} = \dot{m} Cp \Delta T \tag{3.2}$$

$$\dot{m} = \rho_{coll} V_c A_c \tag{3.3}$$

Temperature change with in collector is the difference between the inlet ambient temperature also efficiency of the collect within or defied as flow in equation (3.4 and 3.5):

$$\mathbf{\Delta T = T_1 - T_0} \tag{3.4}$$

$$\boldsymbol{\eta}_{\mathbf{coll}} = \frac{\dot{\mathbf{Q}}}{\mathbf{A_{coll} G}} \tag{3.5}$$

The main parameter affecting the performance of the chimney is defined by its height, and shape chimney in this paper two chimney models are used; cylindrical and divergent. The efficiency of the cylindrical chimney is presented by Equation (3.6) [63]:

$$\boldsymbol{\eta_{ch} = \frac{P_{total}}{\dot{Q}} = \frac{gH_c}{C_p T_a}} \tag{3.6}$$

Efficiency of the chimney for divergent chimney: Due to differences between the chimney's entry and exit areas, the diverging angle of the chimney significantly affects the chimney's efficiency as shown in Equation 3.7.

$$\boldsymbol{\eta_{ch} = \frac{gH_c}{C_p T_a}\left(\frac{A_2}{A_1}\right)} \tag{3.7}$$

The inlet and out let velocity of divergent chimney is different because of the diffuse angle from the continuity equation (3.8), the outlet velocity of the divergent chimney can calculated as follow:

$$\boldsymbol{V_{ch,in} . A_{ch,in} = V_{ch,out} . A_{ch,out}} \tag{3.8}$$

The power output of the solar chimney power plant depends on the efficiency of the collector, chimney and efficiency of the turbo generator. From previous researcher the turbine efficiency is from 80% up to 90%

The overall efficiency of the solar chimney power plant is the product of collector, chimney and turbo generator efficiency it represented as follow in equation (3.9):

$$\boldsymbol{\eta_{ovl} = \eta_{coll}.\eta_{ch}.\eta_t} \tag{3.9}$$

The estimated power output of the solar chimney power plant is calculated by equation 3.10 as[37]:

$$\mathbf{P_{out} = G.A_{coll}.\eta_{ovl}} \tag{3.10}$$

The experimental study used the equations listed above from 3.1 to 3.10 to estimate the power plant's performance.

CHAPTER FOUR

4 RESULT AND DISCUSSION

This study's initial focus is to evaluate the performance of the solar chimney power plant on a small scale to investigate the difference between cylindrical and divergent chimney power plants. the experiment was done in Addis Ababa, Addis Ababa University Institute of Technology. The weather condition was windy also most of the time average solar radiation intensity was recorded. The goal of the experimental inquiry was to assess the effectiveness of the chimney model by determining the temperature and air velocity at various locations. Therefore, the result was evaluated using the parameters of temperature variation over time, power output, solar radiation, efficiency and air velocity.

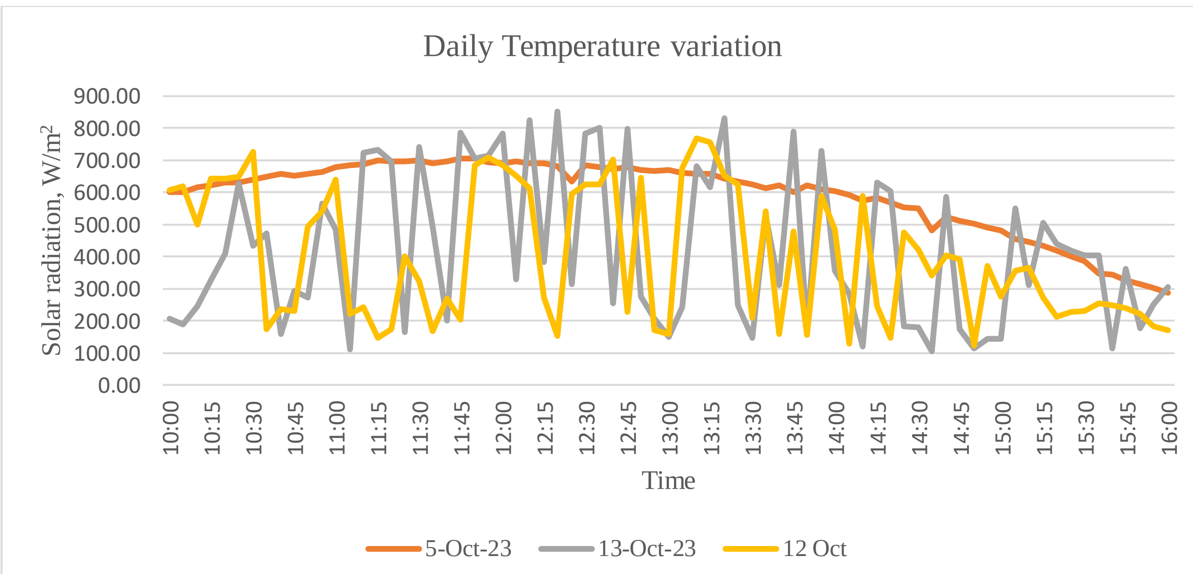


Figure 4.1 Daily solar radiation of experimental place.

Figure 4.1 above depicts the sun radiation measured on three distinct days. The data was taken on 05, 12 and 13 October 2023. According to the graph, 851 W/m2 of solar radiation was observed during midday on October 13, 2023, at 12:20. However, the data gathered on October 5 showed high average sun radiation even though it was only average solar energy On October 5, 2023, the graph revealed that in the morning, there was average radiation and a tiny rise up to the mid-day maximum temperature of 705 ^{o}C, but after that, the solar intensity progressively decreased due to the sun nearing sunset. However, on October 12 and 13, 2023, due to the cloud effect, there were fluctuations in the data. As a result of this unstable solar radiation, the temperature difference at the collector output decreases, and thermal efficiency decreased.

4.1 Temperature Variation

The temperature variations of the cylindrical and divergent chimney models' collector outlet, ambient, and absorber temperatures are discussed here. since the two models' collector configurations are the same, so collector temperature recorded was shown most likely the same. However, there is fluctuation in Temperature especially on the collector's outlet because of the factors like the wind direction and orientation of the prototype. Figure 4.2 illustrates that the outlet temperature of the collector was recorded most likely the same throughout, the average was 32.34 ºC and the highest was 36 ºC. Also, the absorber temperature recorded the highest temperature which was 67 ºC. On the contrary, the temperature variation taken on 12 and 13 October 2023 was recorded as shown in Figures 4.3 and 4.4. the collector outlet temperature of cylindrical and divergent are recorded most likely the same it ranges from 26 to 41.7 ºC and is relatively high. Due to increased radiation, the collector outlet temperature rises in Figure 4.4 from 11:45 to 12:50 then it starts to fall. The maximum recorded temperature of 41.7 ºC happened at 12:25 in the afternoon.

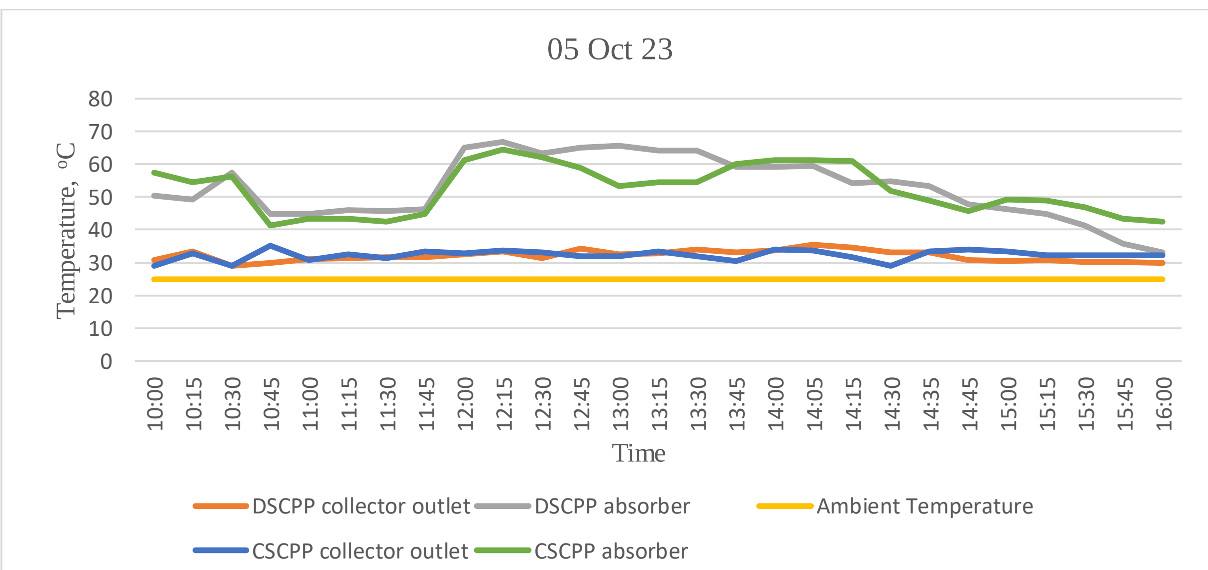


Figure 4.2 Daily temperature variation of the power plants

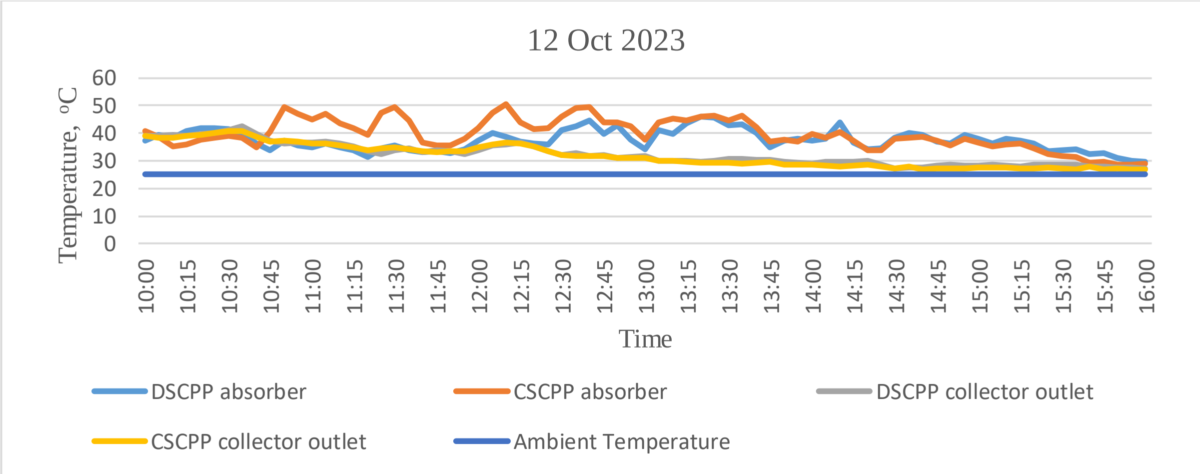


Figure 4.3 Daily temperature variation of 12 October 2023

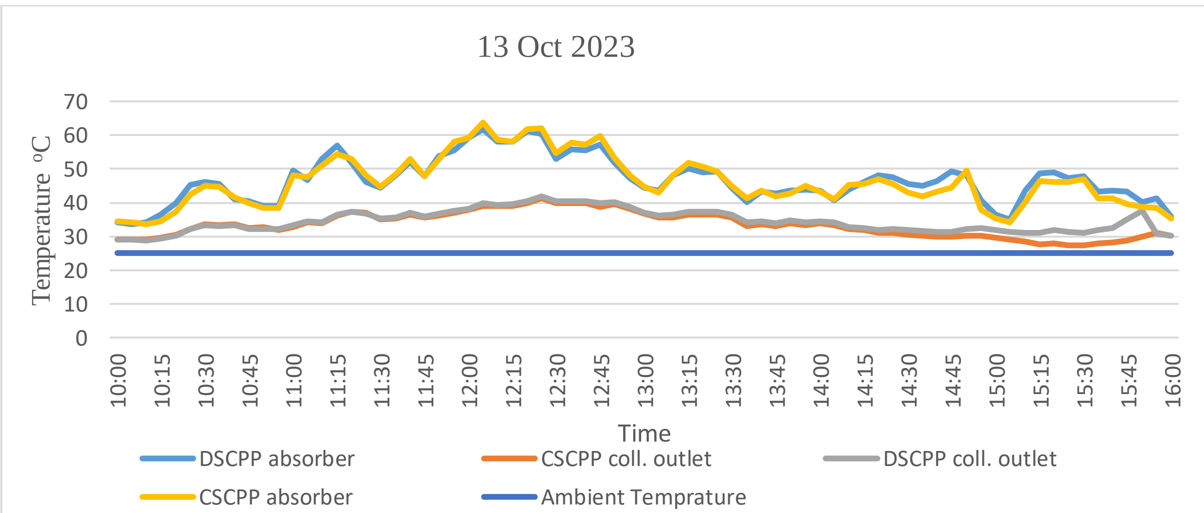


Figure 4.4 Daily temperature variation of 13 October 23

As a result, the maximum temperature recorded on the black rubber absorber in the graph between 4.2 and 4.4 serves to store temperature and contributes to power output growth. The temperature change was modest over three days, which had a substantial influence on internal energy, but the impact of the absorber was also apparent.

4.2 Solar Radiation with Power Output

The plant's output power is closely correlated with solar radiation. Figures 4.5, 4.6 and 4.7 depict the power output of the cylindrical solar chimney power plant (CSCPP) and the divergent solar chimney power plant (DSCPP) regarding variations in hourly solar radiation. During those three days when solar radiation increased the power output, largely comparable conditions were seen.

Even when the opposite occasionally occurs, this is due to the velocity increase. It was obvious, particularly on October 5, 2023, that power output increased despite a decline in solar radiation. Because of variations in air velocity and sun intensity.

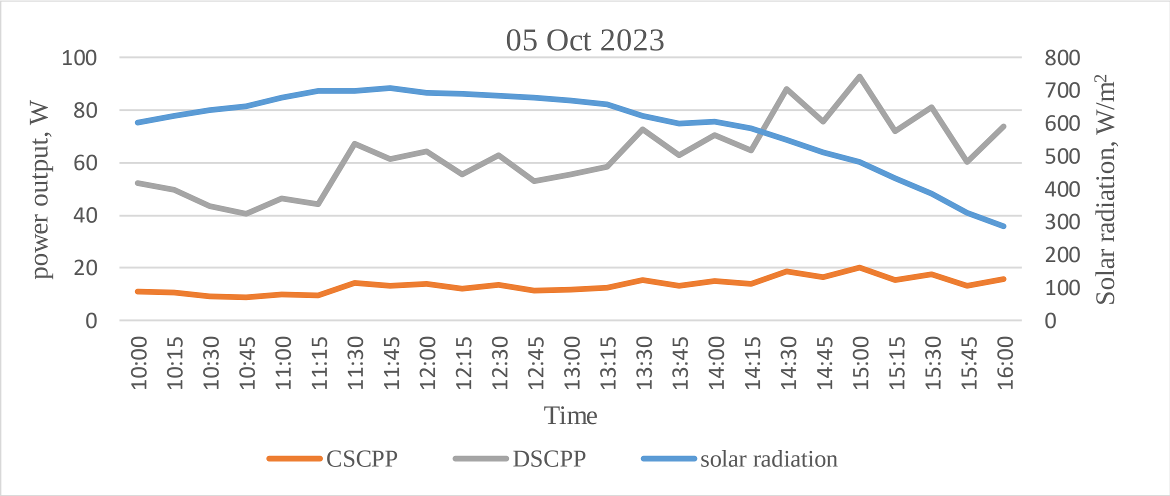


Figure 4.5 Power output variation with solar radiation

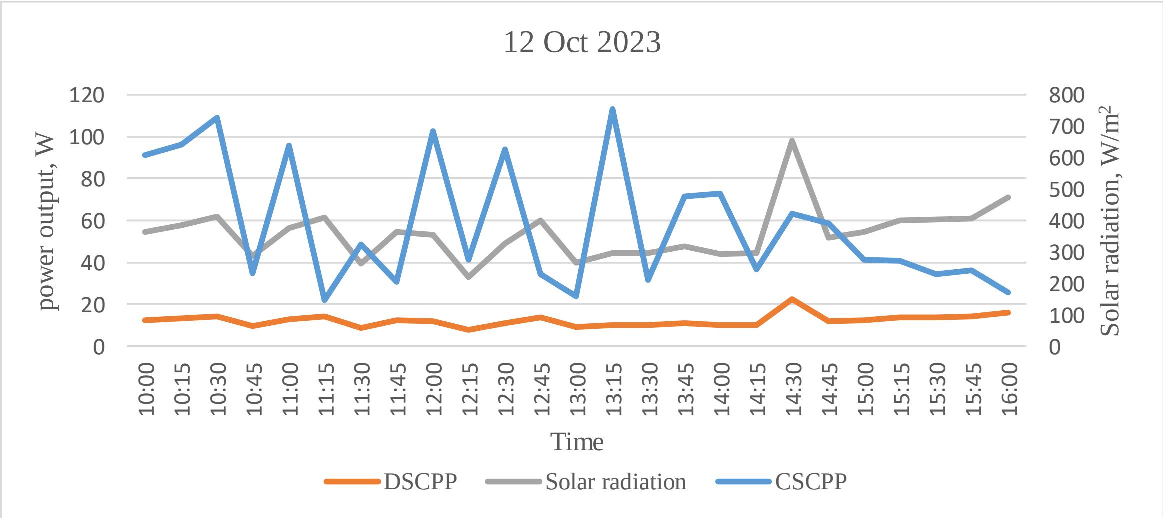


Figure 4.6 Daily Power output difference with the solar radiation variation

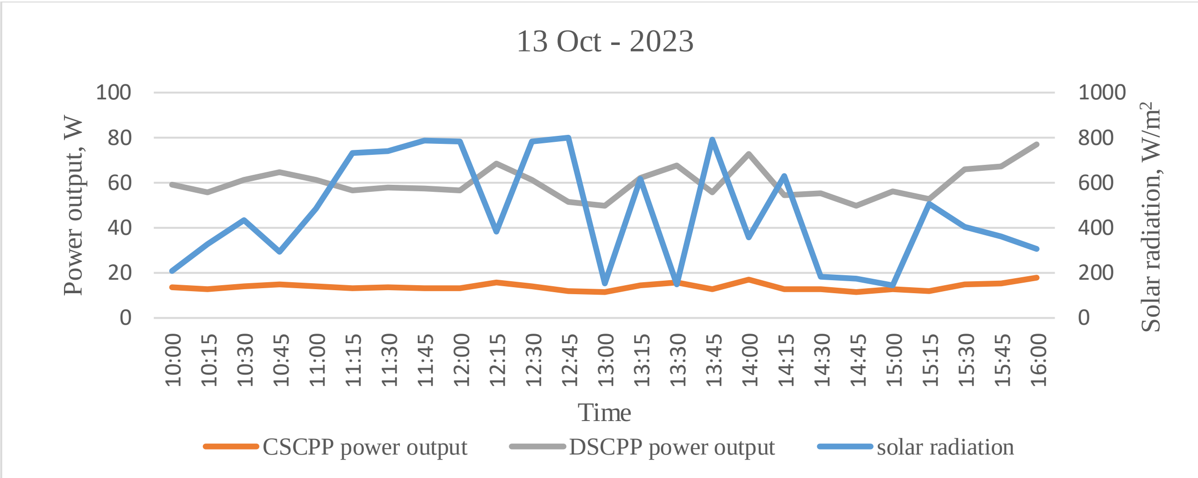


Figure 4.7 Daily Power output difference with the solar radiation variation

The power plant's power production was affected by air velocity throughout the day. The data indicates that power output grows exponentially with velocity. The experiment was conducted in October 05, 12 and 13. Figure 4.10, obtained on October 12, shows that the collector air inlet velocity varies between 0.59 and 1.8 m/s. Also, On Figure 4.6 it observed the highest power generation in the cylindrical and divergent chimneys was noted at 14:30 with 1.8 m/s in the morning, 25 W, and 108.6 W, respectively. On the other hand, on October 5 and 13, the velocity varied between 0.7 and 1.6 m/s. Furthermore, divergent chimneys diffused in 2^{o}, which was the primary factor causing a significant variation in power output. The data also shows that wind speed has a major influence on increasing the amount of work done. Hence the generated power increased linearly with velocity due to the mass flow rate increase caused by the velocity increment.

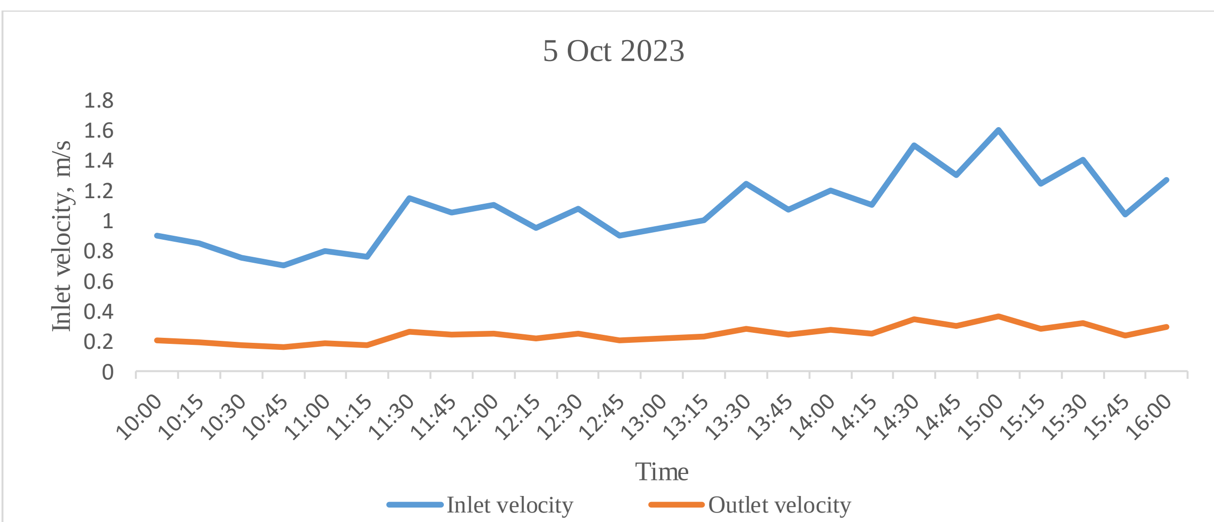


Figure 4.8 Daily variation of inlet and outlet velocity of divergent Chimney

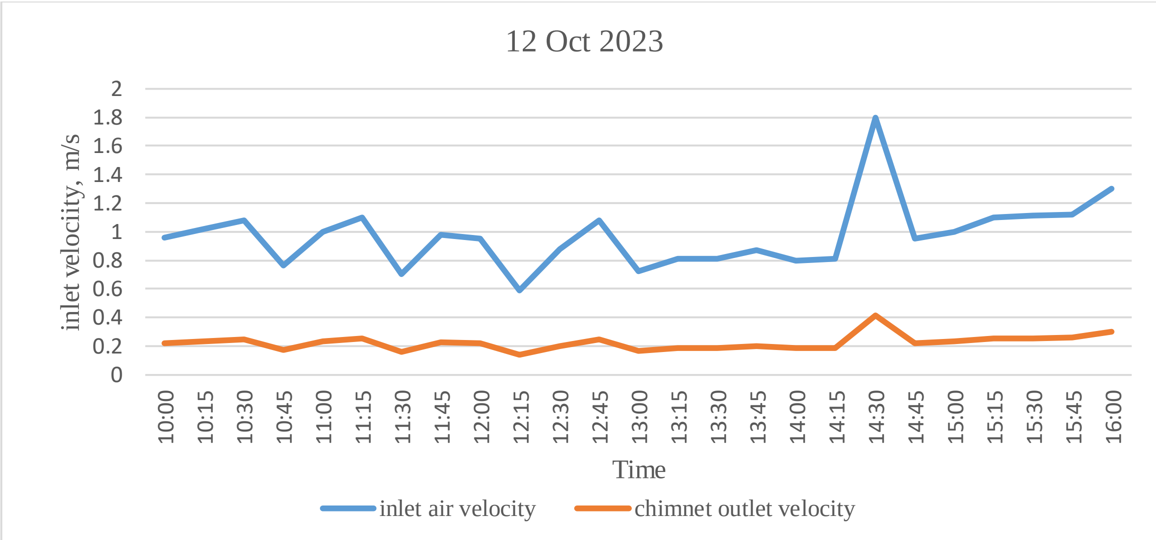


Figure 4.9 Daily variation of inlet and outlet velocity of divergent Chimney

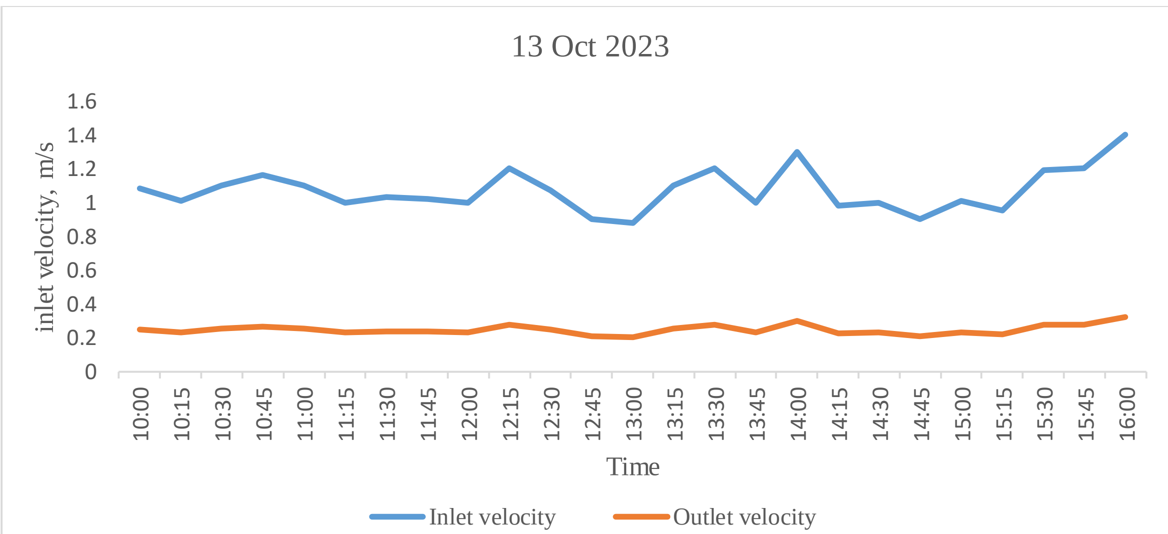


Figure 4.10 Daily variation of Inlet and outlet velocity of divergent Chimney

The entrance velocity recorded at the collector inlet and the outlet velocity difference resulting from the chimney shape are depicted in Figures 4.8, 4.9 and 4.10. Because of the cylindrical chimney's constant diameter throughout its height, the temperature at the input and outlet are the same. The outlet velocity of the divergent chimney calculated by equation 3.8 on Oct 05, 12 and 13 the highest inlet and outlet velocity was 1.6 m/s, 1.8m/s, 1.4 m/s and 0.36 m/s, 0.41 m/s, 0.32 m/s respectively. Figure 4.10 shows the highest inlet wind velocity recorded on the 12 of October at 14:30. Thus, the outlet velocity increase with the inlet velocity because of the 2° diverging angle.

4.3 Performance comparison

In this experimental study, temperature, wind speed, and global sun radiation were measured. The data analysis result showed that the diverging chimney's efficiency was 35.6%, whereas the cylindrical chimney's was 8%. This led to the divergent chimney DSCPP plant's average overall efficiency increase by 4.35 times CSCPP. The thermal efficiency and overall efficiency of the power plant varies with time and radiation discussed below.

The effect of the power plant's thermal efficiency on the collector of DSCPP and CSCPP on total efficiency is shown below. However, the effectiveness of the collector was the same for both versions due to the similar dimensions and material employed. As a result of the absence of a substantial variation in the collector's performance, as shown in Figure 4.11, one efficiency was taken into account on each day.

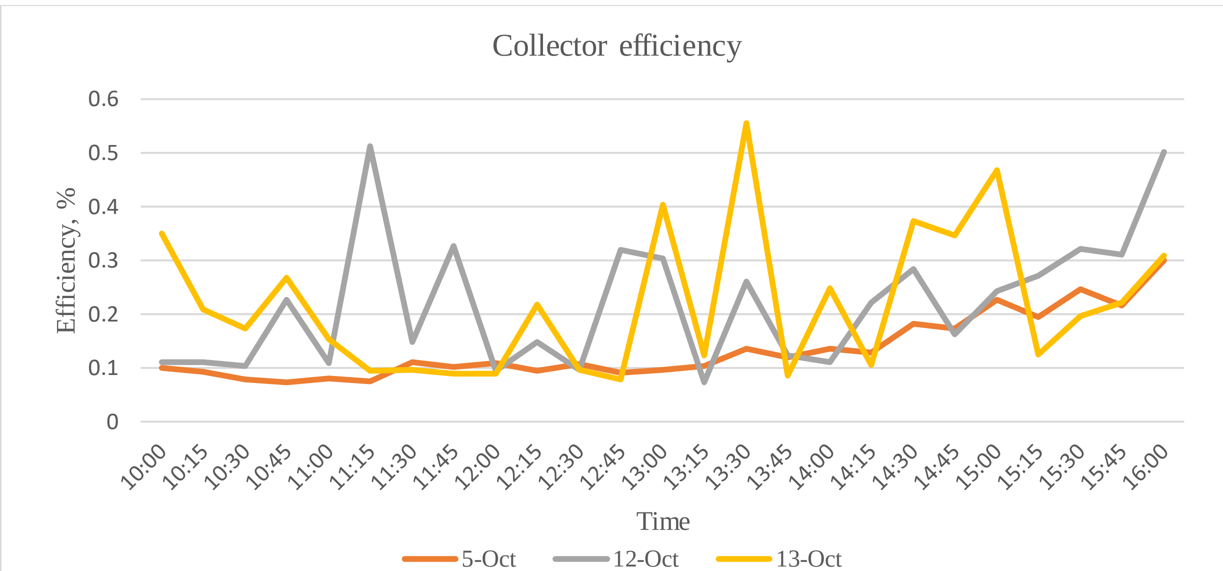


Figure 4.11 Daily thermal efficiency collector of October 05,12,13

however, might have been more consistent owing to oscillations in solar intensity. Due to low solar radiation, low collector performance was recorded at the start of the day on October 5 and 12. On the other side, high efficiency was reported in the morning on October 13th, then progressively dropped and varied throughout the day. However, on October 5th, the performance was extremely consistent. But as seen in the graph, efficiency increases after 15:15 as sun light diminishes. As a result, the study's discovers that wind velocity has a considerable influence on the operation of the SCPP. The thermal efficiency has an impact on overall efficiency of the power plant.

The power plant's total efficiency is evaluated as follows; for the DSCPP and CSCPP using daily sun radiation. Each day, the performance of the two models was assessed and stated.

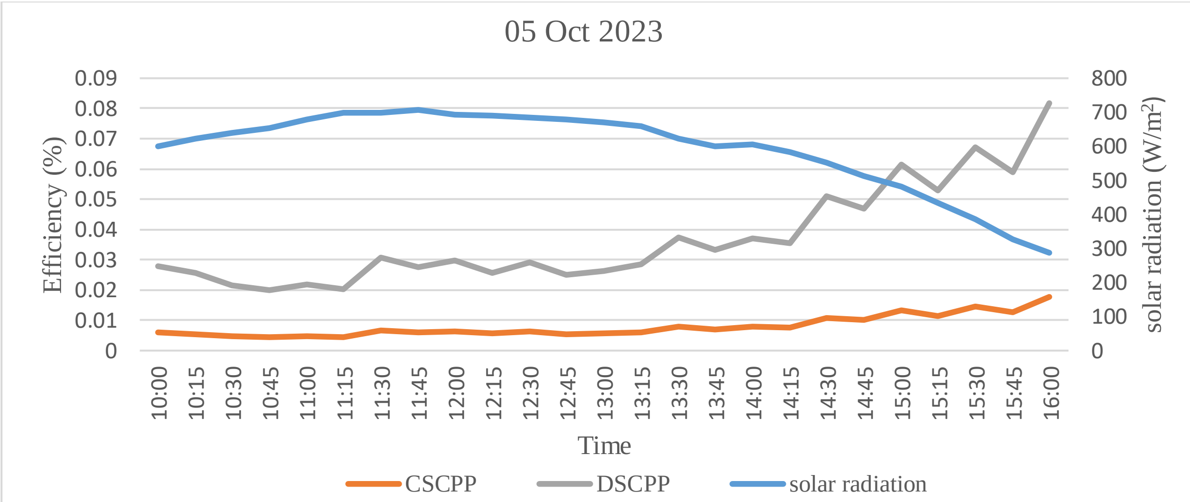


Figure 4.12 Power plants' daily overall efficiency with variations in solar radiation

Figure 4.12 shows that the efficiency of both power plants remained steady from 11:30 to 13:15 at solar radiation, with a high efficiency of 0.2% observed on average. However, when solar radiation drops, efficiency begins to rise. Furthermore, Figures 4.13 and 4.14 demonstrate the variation in efficiency versus radiation in these two days when there was approximately the same change in solar intensity, but there was a cloud, thus the fluctuation appeared. Figure 4.13 shows that there was rather useful solar radiation at the start of the data gathered in the morning, but plant efficiency was poor. However, near the end of the day, when the radiation declines, the projected power production of the plant reduces for two reasons: first, the velocity variation was significant in the afternoon, resulting in a decrease in radiation and an increase in wind speed. The temperature held on the black rubber also aids in maintaining the temperature within the collector. As a result, as shown in Figure 4.13, radiation begins to drop after 14:45, and radiation begins to decrease beginning at 15:15 as power increases.

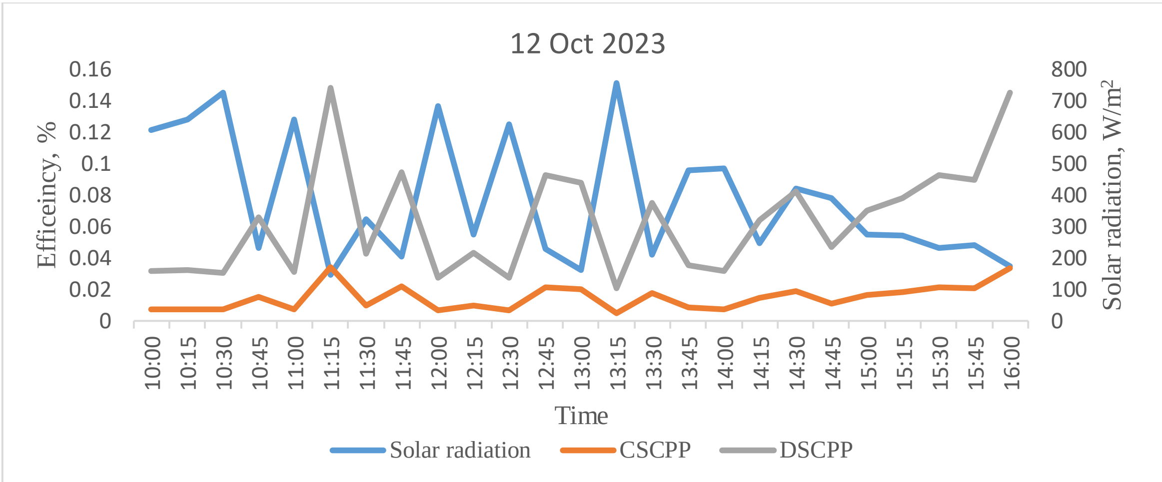


Figure 4.13 Power plants' daily efficiency with variations in solar radiation

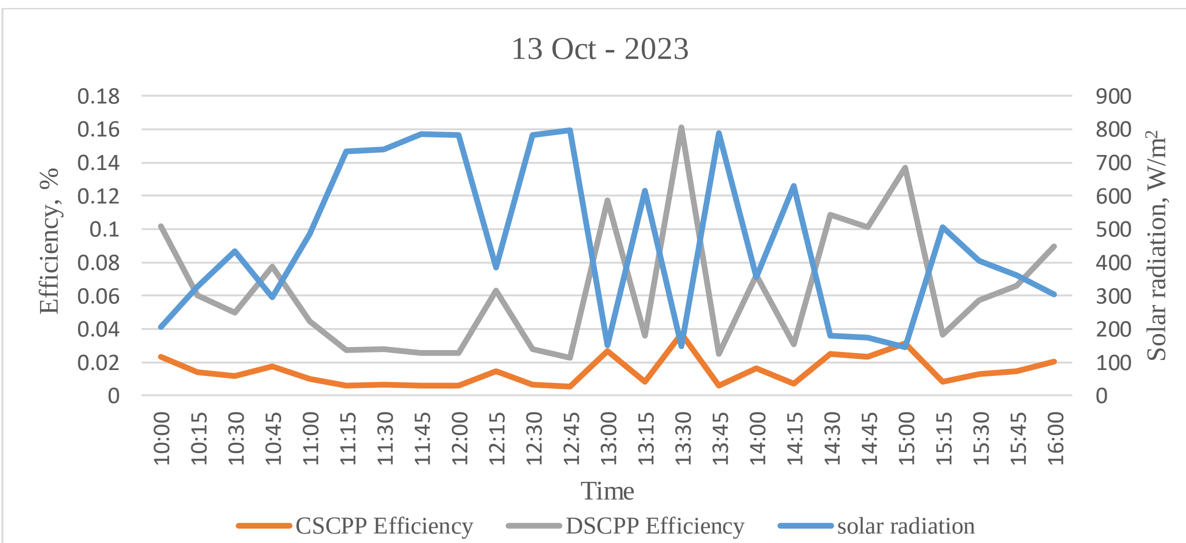


Figure 4.14 Power plants' daily efficiency with variations in solar radiation

The results demonstrate that the radiation had several ups and downs in contrast to the efficiency. This is due to two primary factors: stored heat and air velocity. The collector efficiency rose as a result of stored heat; however, the collector temperature did not drop when radiation fell due to the prior high radiation. Furthermore, the experiment witnessed an increase in mass flow rate due to the rise in air velocity, which increased collector efficiency and, as a result, an overall efficiency improvement.

Table 4.1 illustrates the summary of the average overall efficiency of the power plants, it was 1.9 % DSCPP, and 0.44% CSCPP. The average power output of CSCPP and DSCPP was 5.29 W and 23.6 W respectively.

Table 4.3.1 Daily Average performance of CSCPP and DSCPP

Day	% η_o, CSCPP	% η_o, DSCPP	power output (CSCPP), W	power output (DSCPP),W
5-Oct-23	0.0030	0.0140	5.1200	23.8881
12-Oct-23	0.0050	0.0217	4.7000	20.4670
13-Oct-23	0.0053	0.0232	6.0524	26.4638
Total Average	**0.0044**	**0.0197**	**5.2908**	**23.6063**

4.4 Validation

Figure 4.15 illustrates the variation in power output for cylindrical and divergent chimneys at heights of 1.5 meters, 2.5 meters, and 3.5 meters. The analysis was conducted by altering only the chimney height, while other parameters of the power plant remained constant. The highest power output is observed at 14:30, corresponding to peak solar radiation at that time. The divergent chimney at a height of 3.5 meters theoretically achieved a power output of 152 W. This theoretical value highlights the potential difference, as the actual experiment involved only two chimneys with a height of 2.5 meters; the 1.5-meter and 3.5-meter heights were used for comparative purposes based on theoretical calculations.

The parameters from the actual experiment were applied with daily time variations. It is important to note that the experiment was not conducted under controlled conditions, and various factors such as environmental conditions, wind direction, material properties, instrument calibration, and others may have influenced the results. Despite these variables, the graph effectively demonstrates the impact of chimney height on power output for both divergent and cylindrical chimneys.

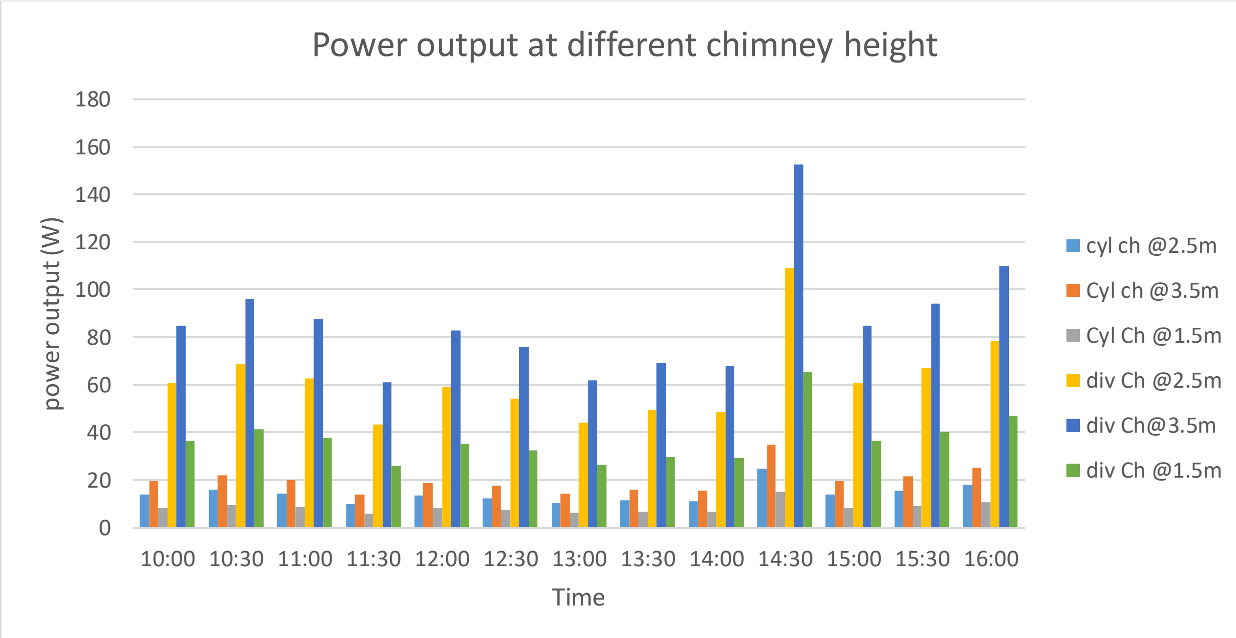


Figure 4.15 power output of divergent and cylindrical chimney at different height

This study focuses on altering only the chimney height while keeping all other parameters constant to simplify the analysis. Data were collected using a uniform collector diameter, evaluating both 0° and 2° diverging angles with varying chimney heights. The findings indicate that divergent chimneys significantly enhance power output. Specifically, increasing the height from 1.5 meters to 2.5 meters results in an average power output increase of 66.6% for both cylindrical and divergent chimneys. Comparing the reference height of 2.5 meters to 3.5 meters shows a 40% increase in power output. Moreover, a 2.5-meter-high divergent chimney produces 3.1 times the power of a 3.5-meter cylindrical chimney. Additionally, a 1.5-meter divergent chimney demonstrates an 86.46% increase in power output compared to a 3.5-meter cylindrical chimney. Overall, divergent chimneys enhance power output by 335.4% at the same height, underscoring the significant impact of chimney configuration regardless of collector dimensions and other variables.

Divergent chimneys have the potential to improve the performance of solar chimney power plants (SCPP). The study discovered that diverging chimneys can enhance airflow velocity, which boosts the power output of the SCPP. The study also discovered shape-controlling characteristics that may be employed to improve the performance of diverging chimneys [64]. The other study achieved power output and efficiency for the pilot plant AR = 1 are 54.3 kW and 0.29%, respectively. However, with the ideal area ratio AR = 4.1, the power output and efficiency are 168.5 kW and 0.83%, respectively, proving the viability of the diverging chimney design. These findings show the importance of chimney geometry, notably the aspect ratio, on the performance of a solar chimney power plant, with the best design resulting in considerable gains in power production and efficiency.[28].

In addition, diverging chimneys have up to 18 times greater theoretical electric generation performance than cylindrical chimneys at the same height ratio. At the largest electric heat load and tallest chimney, a divergent chimney has the potential to generate 0.183 Watt of electric power, while a cylindrical chimney generates only 0.01 Watt. The trials also indicate that a shorter divergent chimney has a higher potential for generating electricity than a taller cylindrical chimney[54]. Despite the fact that the experiment was conducted in a laboratory controlled environment. It does not explore how uncontrollable factors impact power plant performance in other fields.

As a result, this this experiment demonstrated that diverging chimneys of the same height as cylindrical chimneys functions better. This happens in the process of determining the ideal AR of the chimney. According to the study, divergent chimney boosted 4.35 times the same height as cylindrical chimney. and power plant efficiency of 0.4% cylindrical and 1.9% divergent chimney. The influence of velocity on power production is also considerable.

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CHAPTER FIVE

5 CONCLUSION AND RECOMMENDATION

5.1 Conclusion

Research indicates that solar chimney power plants are the future energy solution because of their low cost and simple technology. However, its low conversion efficiency hinders its commercialization. To overcome this change, the configuration of the solar chimney component, mainly the updraft tower, in spite of this there has been limited experimental evaluation of the design of the chimney structure. By comparing the DCSPP and CSCPP, research shows that diverging chimneys are more effective than conventional types at enhancing the performance of solar chimney power plants. However, the study also highlights the need for experimental investigations to analyze the performance of different chimney designs. In this paper, we compare two small-scale solar chimney power plants with the same collector dimension of 2 m. 2^{o} divergent and cylindrical chimneys with comparable chimney heights were developed to compare the performance of the power plant. The study used an experimental technique to discover the study's findings. It was carried out by gathering data from the prototype using instruments and analyzing it using equations.

The performance evaluation of the divergent and cylindrical chimneys has resulted in the following conclusion:

- The temperature variation of the collectors of the DSCPP and SCPP is the same due to the similar dimensional construction and thermal efficiency of the systems.
- The power output from the divergent chimney is 4.35 times that of the same chimney height and cylindrical chimney.
- The manufactured prototype produces an estimated power output of 5.29 W in the cylindrical chimney and 23.6 W in the rectangular chimney.
- The power plant's average overall efficiency for the cylindrical and divergent chimneys is 0.4% and 1.9%, respectively. It grew by 4.1% when compared to the Manzanare power plant.
- The study reveals that velocity has a significant influence on power output performance and has a linear relationship with it.

- Increasing the chimney height from 1.5 meters to 2.5 meters led to an average power output increase of 66.6% for both cylindrical and divergent chimneys. Further increasing the height from 2.5 meters to 3.5 meters resulted in a 40% power output increment
- A 2.5-meter-high divergent chimney produced 3.1 times the power output compared to a 3.5-meter cylindrical chimney.
- A 1.5-meter divergent chimney exhibited an 86.46% increase in power output compared to a 3.5-meter cylindrical chimney.
- Overall, divergent chimneys were found to enhance power output by 335.4% at the same height, emphasizing the significant impact of chimney configuration on SCPP performance.
- The findings highlight the potential of divergent chimneys to improve the efficiency and power output of SCPPs. This enhanced performance is attributed to the increased airflow velocity within divergent chimneys, which boosts the overall power generation capability. The study's results advocate for the adoption of divergent chimney designs in future SCPP implementations to achieve optimal performance and efficiency.

5.2 Recommendation for Future Work

The following recommendations for further work have been made to improve the efficiency of solar chimney power plants:

- Using fully equipped instruments for measuring temperature, velocity, and turbine speed allows for more precise results.
- For observing the actual performance of the plant, create many models with varying heights and diameters to examine the influence of factors.
- For assessment of plant performance, employ all three components of the chimney with the correct instrumentation and test using a generator or measure the speed of the turbine.

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Appendix

Table A.1 October 13 Data collection

Time - Plot 0	G ,W/m^2 -	$T_{div.abs}$, °C	$T_{cyl.1}$, °C	$T_{div.1}$, °C	$T_{cyl.abs}$, °C
10:00	206.65	34.22	29.04	29.05	34.48
10:05	190.28	33.73	28.98	28.99	34.21
10:10	245.72	34.13	29.01	28.92	33.60
10:15	326.09	36.34	29.58	29.39	34.51
10:20	409.85	39.80	30.54	30.35	37.45
10:25	628.95	45.33	32.08	32.14	42.48
10:30	433.55	46.17	33.57	33.48	45.02
10:35	471.98	45.52	33.27	33.13	44.78
10:40	158.51	41.11	33.53	33.29	41.56
10:45	294.05	40.31	32.44	32.31	39.99
10:50	273.21	38.98	32.70	32.29	38.56
10:55	565.38	39.09	32.00	32.10	38.36
11:00	485.07	49.51	32.80	33.21	48.26
11:05	112.74	46.70	34.21	34.43	47.66
11:10	722.01	53.03	33.97	34.12	50.99
11:15	731.92	56.98	36.08	36.47	54.51
11:20	695.49	51.79	37.23	37.24	52.87
11:25	164.07	46.15	36.92	36.73	48.11
11:30	739.90	44.36	35.16	35.29	44.72
11:35	493.64	48.14	35.21	35.66	48.33
11:40	201.41	52.09	36.47	36.94	52.99
11:45	786.59	47.97	35.73	35.77	47.94
11:50	706.13	53.83	36.32	36.73	53.03
11:55	713.58	55.48	37.06	37.55	58.19
12:00	781.83	59.21	37.83	38.19	59.21
12:05	328.95	61.69	38.99	39.86	63.84
12:10	823.68	58.09	39.15	39.44	58.60
12:15	383.63	58.14	39.12	39.69	58.10
12:20	851.77	61.11	39.92	40.54	61.77
12:25	313.62	60.37	41.30	41.74	61.93
12:30	781.91	52.99	40.01	40.47	54.60
12:35	799.95	55.89	40.02	40.46	57.91
12:40	253.40	55.60	39.95	40.35	57.19
12:45	796.82	57.09	38.86	39.77	59.85
12:50	274.58	51.79	39.64	40.08	53.21
12:55	206.97	47.30	38.27	38.65	48.14
13:00	150.19	44.56	36.76	37.06	44.59

13:05	242.58	43.62	35.55	36.04	43.03
13:10	682.07	48.00	35.60	36.45	48.13
13:15	615.81	50.19	36.45	37.43	51.93
13:20	830.15	48.85	36.43	37.35	50.58
13:25	249.08	49.14	36.59	37.29	49.17
13:30	148.15	44.50	35.75	36.34	45.07
13:35	525.09	40.29	33.11	34.07	41.18
13:40	311.34	43.29	33.57	34.37	43.61
13:45	789.25	42.64	33.19	33.99	41.92
13:50	171.83	43.53	33.89	34.74	42.58
13:55	730.23	43.74	33.38	34.08	44.91
14:00	356.22	43.47	34.02	34.43	43.36
14:05	285.44	40.78	33.33	34.10	41.00
14:10	120.33	43.87	32.09	32.86	45.17
14:15	630.44	46.08	31.81	32.52	45.68
14:20	604.70	48.10	31.19	31.97	46.91
14:25	183.08	47.41	31.07	32.14	45.43
14:30	180.34	45.46	30.63	31.84	43.09
14:35	105.53	45.07	30.29	31.60	41.96
14:40	587.30	46.44	29.96	31.25	43.18
14:45	174.59	49.35	29.99	31.43	44.47
14:50	115.70	48.18	30.27	32.21	49.52
14:55	145.13	40.70	30.21	32.35	37.96
15:00	144.82	36.60	29.63	31.91	35.38
15:05	549.50	35.03	28.99	31.47	34.17
15:10	312.64	43.51	28.50	31.16	40.24
15:15	506.66	48.58	27.58	30.99	46.35
15:20	440.45	48.98	27.92	31.84	46.27
15:25	418.89	47.27	27.38	31.42	46.10
15:30	404.83	47.71	27.36	31.18	46.89
15:35	403.79	43.28	27.85	31.98	41.16
15:40	113.25	43.56	28.30	32.45	41.17
15:45	361.58	43.40	28.75	34.91	39.57
15:50	178.03	40.28	29.99	37.67	38.87
15:55	252.60	41.33	30.95	34.80	38.52
16:00	305.04	35.88	30.30	30.21	35.38