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Optimizing Solar Chimney Power Plants: Unveiling the Superiority of a Different Degrees Converging Chimney and Different Collector Configuration

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ABSTRACT:

Continuous growth in population and globalization are causing fast exhaustion of natural resources and thus shifting focus toward renewable sources of energy. Solar Chimney Power plant has proven its capability to produce power from solar energy long ago. Although it could not last longer because of structural weakness and harsh weather conditions. Since then, structural bottlenecks could be handled and the technology could be explored in areas where wind velocity is low, such as India. In this paper, a comprehensive review and theoretical investigation have been done to optimize the Solar Chimney Power Plant (SCPP). Convergent chimney design has been found to produce less dead load and seismic load in comparison to basic chimney design when calculated. Though wind load has been found to be higher in a convergent chimney, since in India, specifically northeast India, there is low wind velocity, a convergent chimney design has been undertaken, and the parameters of the collector and the degree of convergence of the chimney are optimized.

Keywords: Solar Chimney Power Plant, Chimney Design, Optimize Convergence Angle, Collector Configurations.

1. INTRODUCTION

Continuous growth in population and globalization are causing fast exhaustion of natural resources and thus shifting focus toward renewable sources of energy. Environmental climate change has become a burning topic worldwide, and researchers are intensifying their search to use different energy sources to cope with the necessity. Therefore, it is important to develop and or improve technologies utilizing renewable and clean energy sources like solar, biomass, tidal, hydrogen, and geothermal energy to solve these problems. Solar Chimney Power Plant (SCPP) technology which harnesses solar energy is one of these. In an SCPP solar energy creates an updraft of air because of buoyancy force which is converted to power. Although Experimental work has been started forty years before and a large number of theoretical and experimental work has been cited in the literature still there is scope for further research in the field of stable design, efficiency, sizing, etc. In this paper, a review of the literature with the comparison of different designs of Chimney has been done and also a theoretical investigation of a convergent chimney type of solar chimney power plant to get optimized convergence of Chimney design as well as the design of solar collector for maximizing power production.

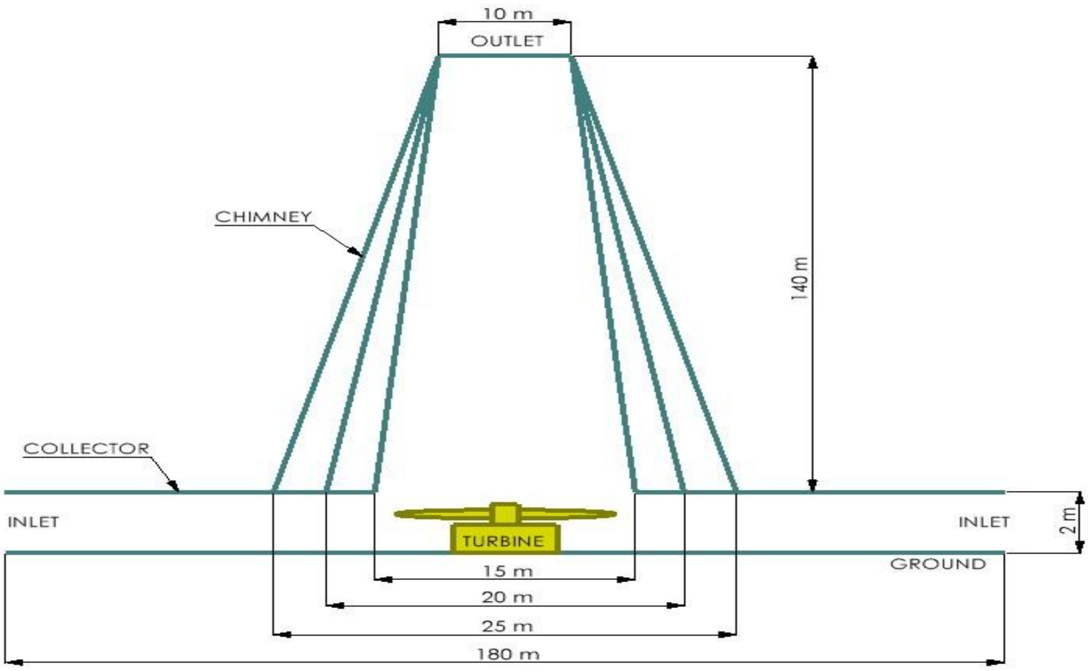
The solar chimney power plant (SCPP) system was proposed in the late 1970s by Professor J. Schlaich and tested with a prototype model in Manzanares, Spain in the early 1980s [1,2]. The chimney tower was 194.6 m high, and the collector diameter was 244 m. Schlaich et al. [1] studied the transferability of the experimental data of the prototype in Manzanares to large power plants (5, 30, and 100 MW). Fundamental Investigations of the Spanish System were reported by Haaf et al. [2] in which a brief discussion of the energy balance, design criteria, and cost analysis was presented. Kulunk [3] produced a micro-scale electric power plant of 0.14 W in Izmit, Turkey. Mullet [4] presented an analysis to derive the overall efficiency of the solar chimney. Padki and Sherif [5,6] conducted an investigation of the viability of solar chimneys for medium to large-scale power production and power generation in rural areas. Yan et al. [7] reported a more comprehensive analytical model in which practical correlations were used to derive equations for the air flow rate, air velocity, power output, and thermofluid efficiency. Kreetz [8] presented a numerical model for the use of water storage in the collector. His calculation showed the possibility of a continuous day and night operation of the solar chimney. In the work crafted by Maia et al. [9] the impact of the wind stream inside the framework is concentrated on mathematical techniques, and it is tracked that the length and chimney diameter are the main factors, which raise the proficiency of the SCPP. Koonsrisuk et al. [10] and Alawin et al. [11] have designed a SCPP for power generation and analysis of the model is done numerically in Jordan. The highest velocity, pressure, and mass flow obtained from the chimney are presented with the change in height in a tower. An increase in chimney height produces higher power output. Optimal chimney height for power generation has been investigated by Shahi et al. [12] found that a 1000 m chimney can exceed 300 KW and Cuce et al. [13] reported a power output of 134 KW with 0.67% overall efficiency from a 500 m chimney. Zhou et al. [14] have shown the optimal value for chimney height can vary depending on the collector diameter. Ghorai et al. [15] investigate Comparative Analysis of Solar Chimney Power Plant Chimney Design: Performance Evaluation and Material Cost Comparison. Although in this paper a divergent and sudden expansion types of chimney design gives better efficiency and lower cost of material, from the experience gained during first experimental SCPP at Mazarine which lasted only 7 years, it is necessary to opt for a chimney design which will be more stable from the point of view of fluid dynamics. A convergent type of chimney design can give comparatively a more stable design from the point of view of wind velocity.

2. OBJECTIVE

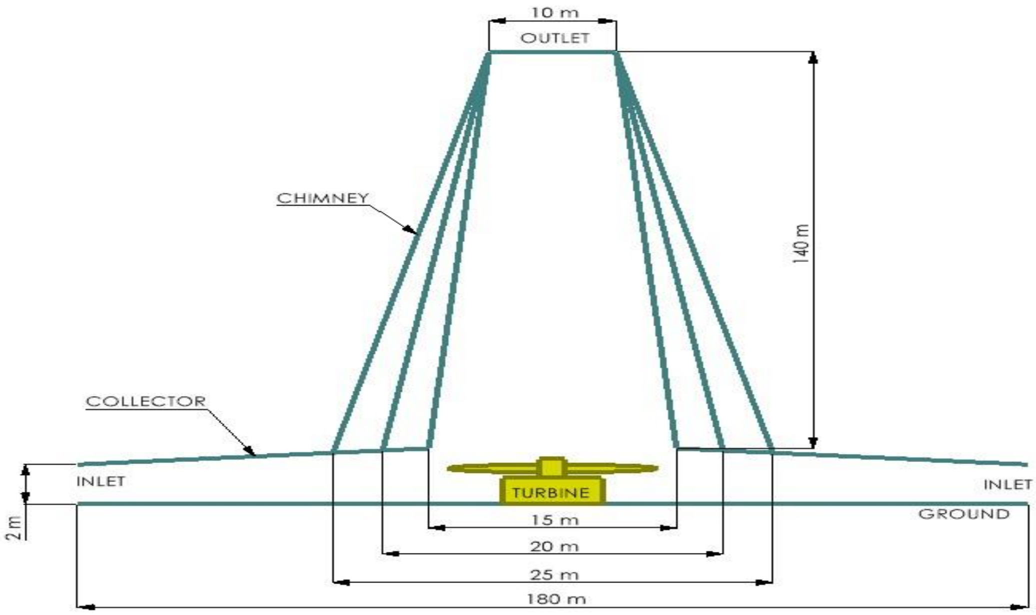
The main objective of the current work is to do the theoretical analysis of a Solar chimney power plant with a convergent chimney design. Parameters include angle of convergence, Chimney height, etc. Theoretical analysis is also proposed to find out optimized collector design out of basic, divergent, and convergent collectors. Collector diameter is also will be optimized. Also, optimized the load capacity of dead load, wind load, and seismic load.

3. WORKING PRINCIPLE OF SCPP

The main geometric parameters of the SCPP are the height of the collector from the ground surface at entry (H_{coll} = 2m), the height of the collector from the ground surface at the middle (H_{coll} = 3m), collector diameter (D_{coll} = 180m), chimney diameter (D_{ch} = 10m), chimney height (H_{ch} = 140m). The large collector area is typically a circular structure made of transparent material such as glass or plastic. Sunrays enter the collector area and heat the air which is near the ground. The heated air becomes less dense and rises due to the natural principle of convection creating a temperature gradient within the collector area, with the air at the bottom being warmer than the air at higher levels. The converging walls at the base of the chimney create a bottleneck effect for the rising air, effectively concentrating and accelerating the flow of air toward the center. When the heated air comes into the middle of the chimney, which is usually a tall and converged structure. As the hot air is funneled into the chimney, it is forced to move upward due to the chimney effect, where the hot air inside the chimney is replaced by cooler, denser air from the surroundings. When the hot air rises through the chimney, it passes through turbines which are located at the base of the chimney. The convergent zone and the focused airflow help increase the velocity of the air, resulting in higher efficiency and power generation. This cycle continues as long as there are sufficient sun rays to heat the air within the collector area and increase the power output of the solar chimney power plant. Nine types of convergent chimneys with different types of collectors are considered in this paper for evaluation of performances which are shown in Figure 1-3.



(a)



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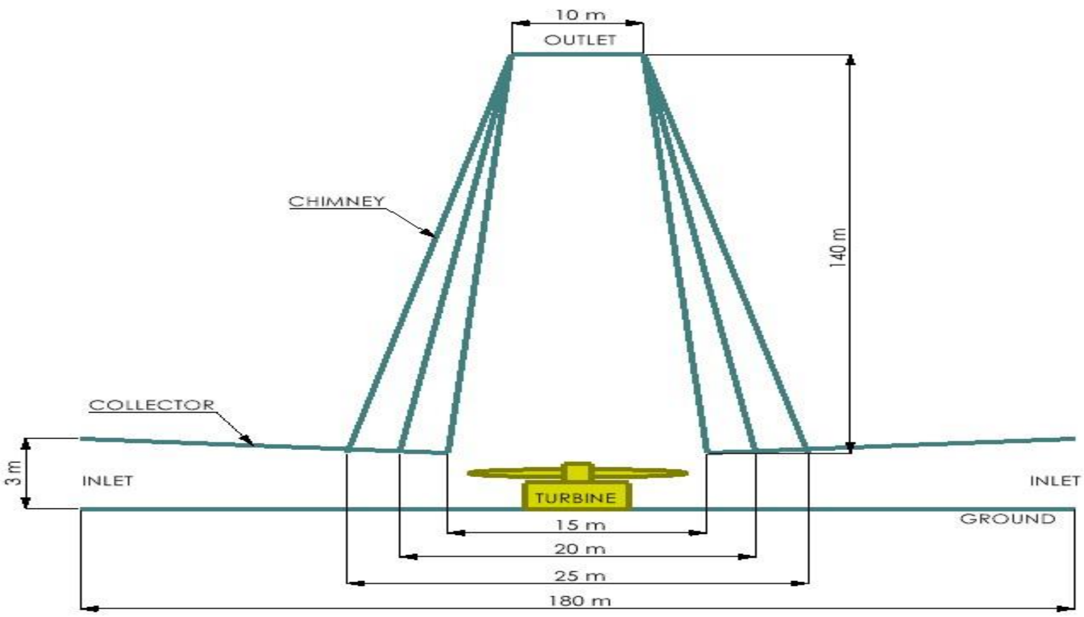

(c)

Figure 1: 2D diagram of Convergent Chimney with (a) Basic Collector, (b) Convergent Collector, (c) Divergent Collector.

4. METHODOLOGY

In the present study, the chimney outlet diameter is kept constant, and the chimney inlet diameter varies according to the chimney's convergence angle in the range of different degrees. Also, the different types of collectors like horizontal or basic collectors, convergent collectors, and divergent collectors, represent the convergent chimney design. By coupled solving of continuity, momentum, energy, and turbulence model equations, regression equations are achieved for mass flow rate, max velocity, max temperature, CB velocity, CB temperature, CB pressure, power output, and system efficiency.

Nomenclature:

A_{ch}	Chimney area, m^2
C_p	Specific heat of air, kJ/kg K
D_{ch}	Chimney outlet dia, m
D_{coll}	Collector dia, m
H_{ch}	Chimney height, m
g	Acceleration due to gravity, m/s^2
G	Amount of solar intensity radiation absorbed, W/m^2
I_s	Solar insolation on collector, W/m^2
r	Radius of the absorber plate, m
T_a	Ambient temperature, K
η_t	Turbine efficiency
η_{coll}	Collector efficiency
V_{ch}	Velocity through the chimney, m/s
ρ_{air}	Ambient air Density, kg/m^3
η_{ch}	Chimney efficiency
T_h	Hot air temperature, K
T_0	Collector outlet temperature, K
ΔT	Temperature difference between hot air and ambient air temperature, K
τ	Transmissivity of the cover
A_{coll}	Area of the collector, m^2

A convergent solar chimney power plant is a type of solar power generation system that utilizes the greenhouse effect to create an updraft of air through a chimney, driving a turbine and generating electricity. The convergent design involves narrowing the collector area towards the base of the chimney to increase the air velocity and improve efficiency. Here's a general methodology for designing and analyzing a convergent solar chimney power plant:

1. Geographical and Meteorological Analysis: Identify potential locations for the solar chimney power plant based on solar radiation levels and other meteorological factors. Gather data on temperature, wind speed, and atmospheric conditions at the chosen site.

2. Solar Collector Design: Choose the type of collector based on the specific design requirements (e.g., horizontal or basic collectors, convergent collectors, etc.). Design the collector area to absorb and store solar radiation effectively. Determine the collector's material properties and thermal characteristics.

3. Computational Fluid Dynamics (CFD) Analysis: Utilize CFD simulations to model the fluid dynamics within the solar chimney system. Implement the continuity, momentum, energy, and turbulence model equations to study the behavior of airflow, temperature distribution, and pressure gradients. Define boundary conditions, including solar radiation input, ambient temperature, and wind speed.

4. Regression Equations: Conduct numerical simulations to obtain data on mass flow rate, maximum velocity, maximum temperature, chimney base (CB) velocity, CB temperature, CB pressure, power output, and system efficiency. Develop regression equations based on the simulation results to establish relationships between various parameters and optimize the system.

5. Sensitivity Analysis: Perform sensitivity analyses to understand the impact of changes in design parameters on the overall performance of the system. Evaluate the influence of collector size, shape, materials, and other factors on the efficiency of the solar chimney power plant.

6. Optimization: Use optimization techniques to find the optimal configuration of the convergent solar chimney design that maximizes power output and system efficiency. Consider trade-offs between different parameters to achieve a balance between performance and cost.

7. Validation: Validate the developed regression equations and simulation results through experimental data or comparisons with existing solar chimney power plants. Fine-tune the model based on validation results to improve accuracy and reliability.

8. Economic and Environmental Assessment: Conduct a feasibility study that includes economic and environmental considerations. Evaluate the cost-effectiveness and environmental impact of implementing the convergent solar chimney power plant.

By following this methodology, engineers and researchers can design, analyze, and optimize a convergent solar chimney power plant to harness solar energy efficiently for electricity generation.

The continuity equation is a fundamental principle in fluid dynamics that relates the mass flow rate of a fluid to its velocity and cross-sectional area within a conduit. In the context of designing a solar chimney power plant, the continuity equation can be applied to understand and optimize the airflow within the chimney structure, which is a key component of such a power plant.

Continuity equation:

$$\frac{\partial(\rho_{ui})}{\partial_{xi}} = 0 \qquad (1)$$

Navier-Stokes equations can be applied to gain a deeper understanding of the fluid dynamics involved and to optimize the design and performance of the facility.

Navier-Stokes equation:

$$\frac{\partial(\rho u_i u_j)}{\partial_{xj}} = \rho g_i - \frac{\partial P}{\partial_{xi}} + \frac{\partial_{\tau ij}}{\partial_{xj}} \qquad (2)$$

The energy equation can be used to model the heat absorption process within the solar collector.

Energy equation:

$$\frac{\partial(\rho C_p u_j T)}{\partial_{xj}} = \frac{\partial}{\partial_{xj}}\left(\lambda \frac{\partial T}{\partial_{xj}}\right) + \tau_{ij}\frac{\partial_{ui}}{\partial_{xj}} + \beta T(u_j \frac{\partial P}{\partial_{xj}}) \qquad (3)$$

Rayleigh (Ra) number determines the buoyancy-induced flow, which is governed by the following equations:

$$\text{Ra} = \frac{g\beta\Delta T L^3 \rho}{\mu\alpha} \qquad (4)$$

Where, ΔT and L define the maximum temperature difference of the airflow and average collector height respectively. β is the thermal expansion coefficient ($1/T_{max}$) and α is the thermal diffusivity (k/ρC_p). Within the present work, Ra number is found to be highly greater than critical value of 10^9, and thus the flow becomes turbulent in the range of $10^8 < Ra < 10^{10}$.

The equation for the k-ε model:

$$\frac{\partial(\rho k_{ui})}{\partial_{xi}} = \frac{\partial}{\partial_{xj}}\left(\alpha k \mu_{eff}\frac{\partial k}{\partial_{xj}}\right) + G_k + G_b - \rho\varepsilon - YM + S_k \qquad (5)$$

$$\frac{\partial(\rho \varepsilon_{ui})}{\partial_{xi}} = \frac{\partial}{\partial_{xj}}\left(\alpha \varepsilon \mu_{eff}\frac{\partial \varepsilon}{\partial_{xj}}\right) + C_{1\varepsilon}\frac{\varepsilon}{k}(G_k + C_{3\varepsilon}G_b) - C_{2\varepsilon}\rho\frac{\varepsilon^2}{k} - R_\varepsilon + S_\varepsilon \qquad (6)$$

Where, G_k is the turbulence kinetic energy generation for mean velocity gradients. G_b is the turbulence kinetic energy generation for buoyancy. σ_T, σ_K, and σ_ε represent the Prandtl number (turbulent) for T, k, and ε respectively, and C_1, C_2, C_3 are three constants for turbulent model.

Different modes of heat transfer need to be considered in a SCPP. Heat flux is generated from the solar radiation using the process of Solar Ray Tracing and the results are merged with ANSYS FLUENT calculation.

The obtained energy equation:

$$\frac{\partial}{\partial_t}(\rho E) + \nabla.\left(\vec{v}(\rho E)\right) = \nabla.\left(\left(k_{eff}\nabla T - \sum_f h_f \vec{J}_f\right) + \left(\overline{\overline{T}}_{eff}.\vec{v}\right)\right) + S_h \qquad (7)$$

Where, S_h denotes the volumetric heat sources defined by the user, k_{eff} is the effective conductivity, $\vec{J}$ is defined as the diffusion flux of species j.

The radiative transfer equation for Discrete Ordinance (DO) model is given as:

$$\nabla.\left(I(\vec{r},\vec{s})\vec{S}\right) + (a + \sigma_s)I\left(\vec{r},\vec{S}\right) = an^2\frac{\sigma T^4}{\pi} + \frac{\sigma_s}{4\pi}\int_0^{4\pi} I(\vec{r},\vec{S}')\emptyset(\vec{s},\vec{s}')d\Omega' \qquad (8)$$

Where, I is the intensity of solar radiation, $\vec{r}$ is the position vector, $\vec{s}$ is the direction vector, T is the ambient temperature, $\vec{s}'$ is the scattering direction vector, $\emptyset$ is the phase function and Ω' is the solid angle.

Boussinesq model is usually preferred to calculate the density change of air within the system depending on temperature:

$$(\rho - \rho_a)g \approx -\rho_a\beta(T - T_a)g \qquad (9)$$

Where, β is the thermal expansion coefficient, ρ_a is the density and T_a is the temperature of inlet air. The thermal energy input to the SCPP is supplied by the collector part. This energy can be given by the following equation:

$$\dot{Q} = \dot{m} C_p \Delta T \tag{10}$$

Where, $\dot{m}$ is the mass flow, C_p is specific heat and ΔT refers to the temperature rise in the collector from inlet to outlet.

Collector efficiency can also be calculated by dividing $\dot{Q}$ to the total energy falling on collector surface:

$$\eta_{coll} = \frac{\dot{Q}}{A_{coll} G} \tag{11}$$

Where, A_{coll} is the collector area and G is the incoming solar radiation.

Power output is determined through the pressure drop across the turbine (ΔP_t) [16,17]:

$$P_0 = \eta_t \Delta P_t Q_v \tag{12}$$

Where, η_t is turbine efficiency, Q_v is the volumetric flow rate ΔP_t is the average pressure (P_t) at the turbine position based on the findings through CFD research:

$$\Delta P_t = r_t P_t \tag{13}$$

Where, r_t is the turbine pressure drop ratio.

Overall efficiency for a SCPP is given by:

$$\eta = \frac{P_0}{A_{coll} G} \tag{14}$$

By observing the above equations, it can be verified that several factors are responsible for electric power generation. These are both geometrical configurations diameter of the collector, height and diameter of the chimney, space between the ground and collector roof and atmospheric changes that ambient temperature, incident solar radiation and atmospheric pressure.

5.NUMERICAL PROCEDURE AND ANALYSIS

The model geometry is completed in ANSYS WORKBENCH, which is ideal for such research. The present study is carried out numerically using the finite volume based reliable commercially available ANSYS-Fluent 18.1 solver. Here, the 15^0 CFD model is used and preferred to shorten the total iteration period instead of the whole geometry.

5.1. Technique of Discretization:

Algorithm Technique: SIMPLE

Gradient: Green Gauss cell based

Pressure: PRESTO

Momentum: Second order upwind

Turbulent kinetic energy: Second order upwind

Turbulent dissipation rate: First order upwind

Energy: Second order upwind

Discrete ordinates: First order upwind

Under relaxation factor:

Pressure – 0.3

Momentum – 0.8

Turbulent kinetic energy – 0.8

Turbulent dissipation rate – 0.8

Table 1- Boundary Conditions:

Inlet	Pressure- zero-gauge pressure Temperature- 302K
Outlet	Pressure- zero-gauge pressure Temperature- 302K
Collector (semi-transparent cover)	Heat transfers co-efficient- 10 W/m^2K Temperature- 302K
Ground surface (absorber plate)	Heat flux- 0 W/m^2
Chimney (adiabatic wall)	Thickness- 0.00125 m

Boundary condition of the whole system which have been used in our study are given in Table 1. For predicting the correct results, a mesh sensivity test of the SCPP geometry is carried out exhaustively for the different element sizes using constant solar radiation of 1000 W/m^2. Physical properties of air, collector, ground absorber, and chimney which have been used in calculation are given in Table 2.

Table 2- Physical Properties:

Properties	**Air**	**Collector**	**Ground Absorber**	**Chimney**
Material	--	Semi-transparent glass	soil	Aluminium
Density (ρ)kg/m^3	1.225	2500	1500	2710
Specific heat (Cp)J/kg/K	1006.43	840	800	903
Thermal conductivity (K), W/mK	0.0259	0.8	0.364	1.4
Absorptivity	--	0.03	0.9	1.0
Transmissivity	--	0.9	Opaque	Opaque
Thermal expansion coefficient (β), K^{-1}	0.00331	--	--	--
Thickness, m	--	0.004	0.5	0.00125
Refractive index	--	1.526	1.0	1.0
Emissivity	--	0.1	0.9	0.1

The results are compared using the extreme temperature, velocities, velocity at the chimney base, temperature, and rate of mass flow. The mesh size is chosen as M for the element size 0.80 respectively, which are presented in Table 3.

Table 3- Parameters Data:

Parameters Checked	Convergent Chimney with Basic Collector			Convergent Chimney with Convergent Collector				Convergent Chimney with Divergent Collector			
	1^0	2^0	3^0	1^0	1.5^0	2^0	3^0	1^0	1.5^0	2^0	3^0
Max Velocity (m/s)	8.28	10.5	11.32	5.4	13.56	14.34	9.29	11.44	13.5	13.02	5.63
Max Temperature (K)	344.42	352.54	344.81	342.52	452.22	346.91	342.41	384	345.02	399.98	380.67
CB Velocity (m/s)	4.78	8.78	5.09	2.9	11.23	6.8	2.8	9.89	5.2	10.57	3.50
CB Temperature (K)	309.423	314.28	310.567	309.423	342.32	316.82	308.87	329.28	313.28	340.42	330.38
Mass Flow Rate (kg/s)	31.6	36.89	33.23	28.73	41.2	41.7	30.54	32.68	37.07	40.80	22.28

Increasing the angle of convergence in a solar chimney power plant's collector can boost power output by accelerating airflow toward the chimney. This acceleration enhances turbine efficiency, potentially increasing electricity generation. However, a steep angle may cause flow separation, reducing collector efficiency and negating benefits. Engineering challenges arise, as designing a steep-angle collector is complex and costly, demanding meticulous maintenance. Striking a balance is crucial to avoid drawbacks. Changes in solar chimney power plant design should undergo thorough study and modeling to ensure they enhance power output while maintaining system efficiency and reliability.

Increasing the angle of convergence in a solar chimney power plant with a divergent collector is not advisable. The divergent collector, widening towards the chimney, would diminish airflow speed, reduce the temperature differential crucial for power generation, and lower overall efficiency. This design choice introduces engineering challenges, increasing costs and maintenance needs. The convergent shape of the collector is vital for effective heat transfer and airflow acceleration. Altering it negatively impacts the system's performance, making it less efficient and hindering power output. Any modifications to a solar chimney power plant's design should be approached with caution, prioritizing a convergent collector for optimal efficiency and reliable operation.

6.RESULT AND DISCUSSION

A solar chimney power plant, also known as a solar updraft tower, is a renewable energy technology that generates electricity using the natural convection of air heated by the sun. The basic idea is to have a tall chimney with a greenhouse-like collector at the base. Sunlight heats the air in the collector, causing it to rise up the chimney, which drives turbines to generate electricity.

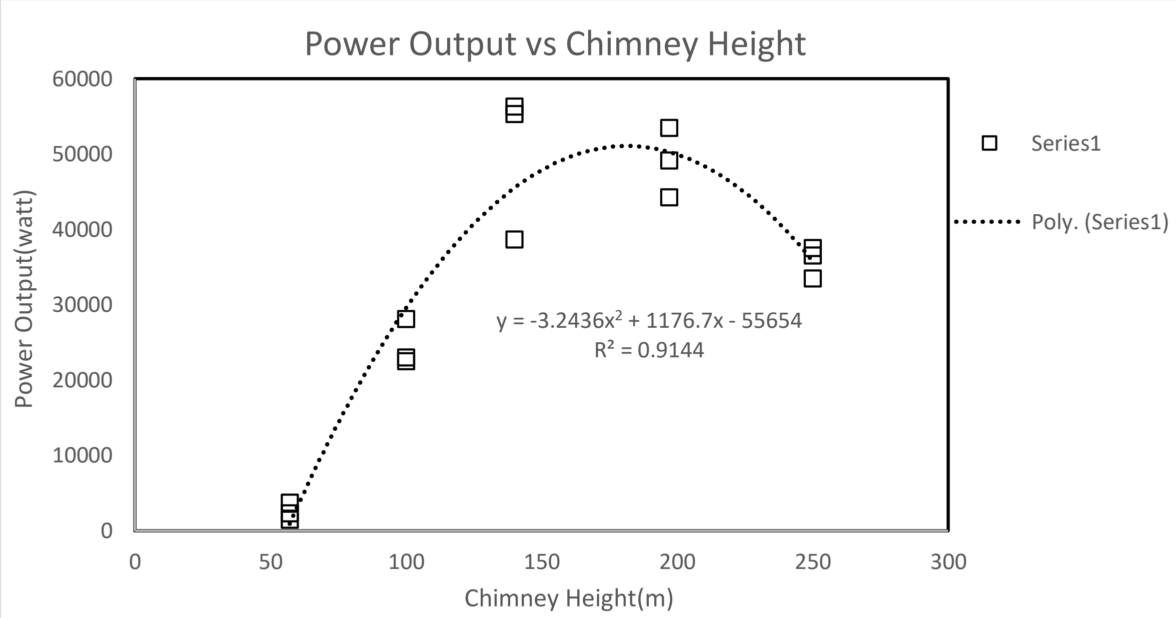

Figure 2- Power Output vs Chimney Height

The power output of a solar chimney power plant does indeed have limits, and it tends to decline as the height of the chimney increases beyond a certain point shown in fig 2. The decline in solar chimney power plant efficiency stems from several key factors. Firstly, the inefficiency of convection arises as the height of the chimney increases, requiring hot air to (Placeholder1)traverse a greater distance, potentially compromising the updraft velocity. This hinders power generation by impeding the buoyant force crucial for the process. Secondly, escalating construction costs and technical challenges accompany the pursuit of greater chimney height, driven by more demanding materials and structural requirements. Beyond a certain point, the investment in taller chimneys yields diminishing returns, as the incremental increase in power output may not justify the economic expenditure. Moreover, the environmental impact of extremely tall chimneys, affecting landscapes and wildlife, poses a critical concern. Balancing these impacts with potential benefits becomes pivotal. Additionally, local wind patterns and weather conditions can influence the solar chimney's performance, limiting its effectiveness in regions with strong winds or unpredictable weather. To optimize solar chimney power plant performance, engineers must consider chimney height, collector size, and local climate. Striking a balance between cost, efficiency, and environmental impact is essential for making this technology economically viable and competitive in the realm of renewable energy generation.

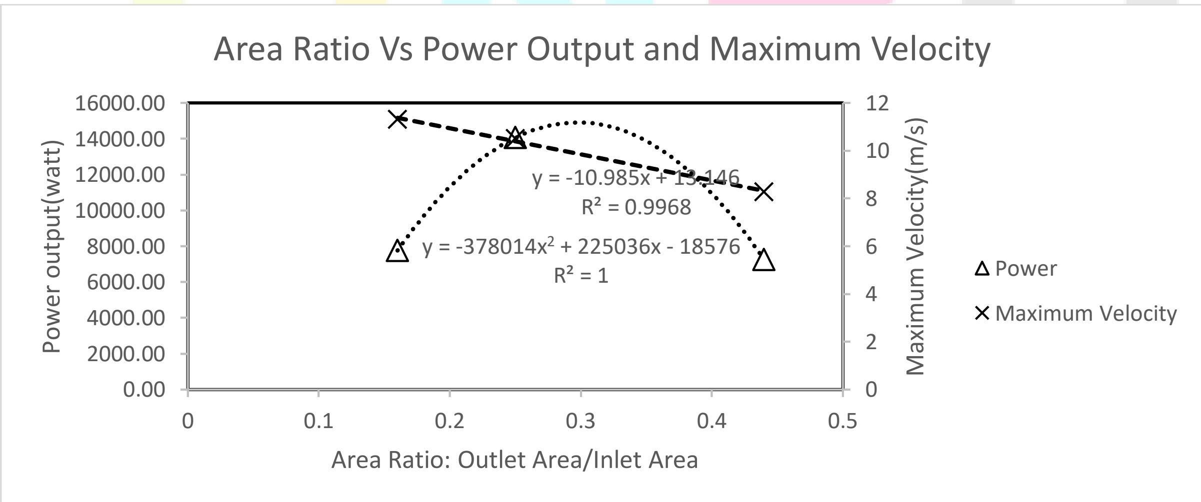

Figure 3- Area Ratio Vs Power Output and Maximum Velocity

Area ratio when increases the power output declines after a certain ratio but for higher chimney height which shows declining power with maximum velocity shows decreasing power output as the area ratio increases for a convergent chimney solar chimney power plant shown in fig 3. In Fig 3, the observed trends highlight crucial aspects of solar chimney performance. Initially, an increasing area ratio boosts power output by facilitating more air heating at the base, resulting in a stronger updraft. However, a decline in power occurs after a certain area ratio, indicating that excessive base area may diminish updraft velocity, leading to reduced power output. Notably, for higher chimney heights, increasing the area ratio may not consistently enhance power generation; instead, it could negatively impact performance, possibly by impeding updraft velocity. Engineers optimizing solar chimney design should consider these findings, emphasizing an optimal balance between base area, chimney height, and power output.

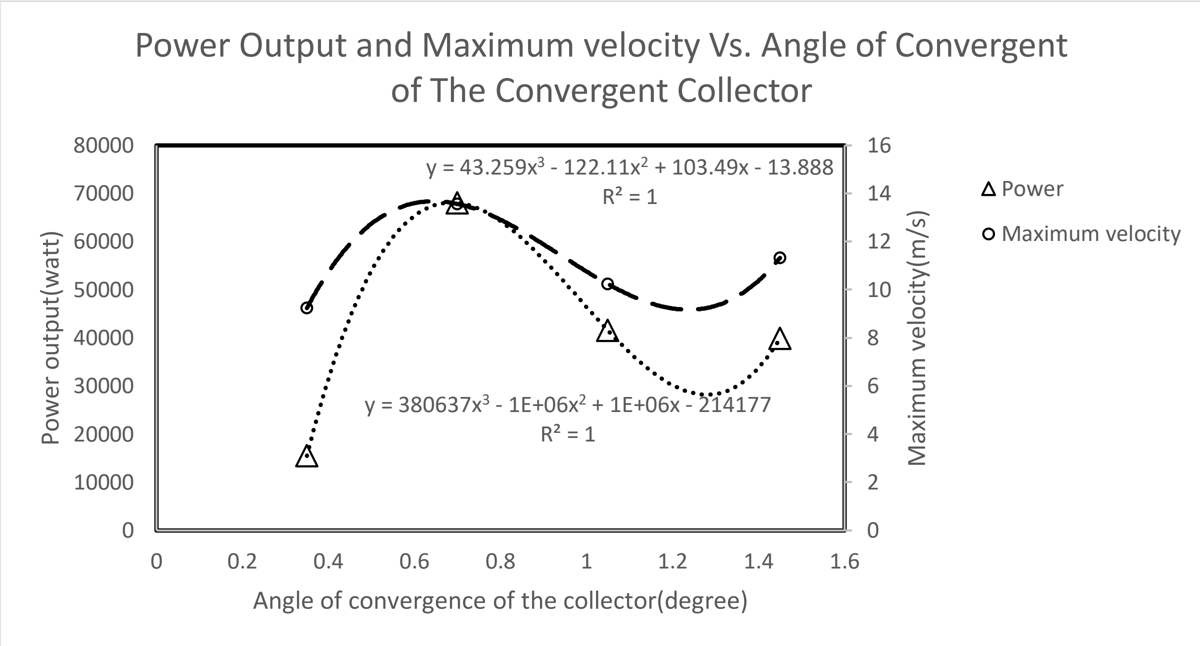

Figure 4- Power Output and Maximum velocity Vs. Angle of Convergent of The Convergent Collector

Figure 4 shows that increasing the angle of convergence initially leads to an increase in power output and maximum velocity, reaching a point of maximum performance, followed by a decline in both, is likely related to the complex interactions of fluid dynamics and thermodynamics in the solar chimney power plant system. Fig 4 reveals critical insights into solar chimney dynamics. The optimal convergence angle plays a pivotal role in maximizing solar energy capture and updraft efficiency. Increasing this angle initially enhances solar radiation absorption, leading to a stronger updraft and higher power output. However, excessive convergence angles may disrupt flow dynamics, causing turbulence and diminishing system efficiency. The transition point, where power output and maximum velocity peak, represents an optimal configuration. Beyond this point, further increases in the convergence angle yield diminishing returns, potentially due to disrupted flow or recirculation. Excessive convergence introduces additional losses through increased friction and turbulence, counteracting the benefits of enhanced solar radiation absorption. The interplay between collector angle, chimney height, and area ratio is complex, with changes in one parameter influencing others, resulting in the observed non-linear behavior. Engineers must carefully balance convergence angles to optimize solar chimney performance, considering the intricate interactions between various parameters.

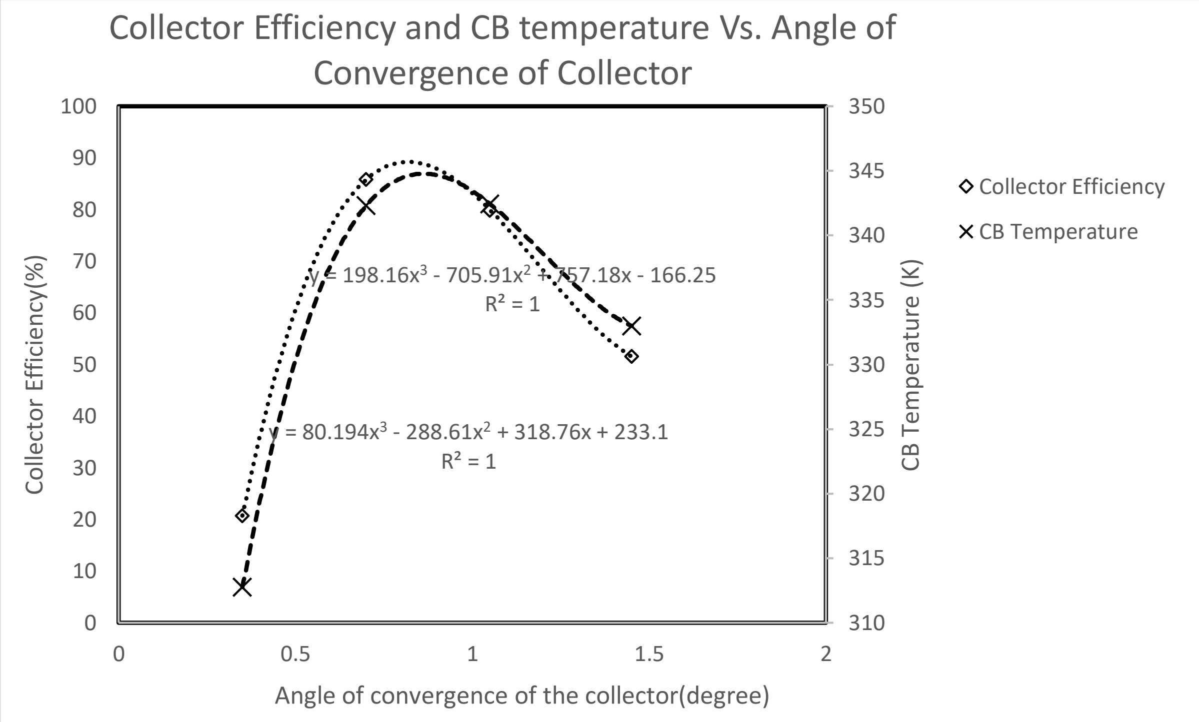

Figure 5- Collector Efficiency and CB temperature Vs. Angle of Convergence of Collector

In a convergent chimney solar chimney power plant, the efficiency of the collector and the temperature of the working fluid (usually air) are critical factors in determining the overall performance. Fig 5 illuminates key aspects of solar chimney performance. Increasing the angle of convergence initially boosts collector efficiency and Collector Base (CB) temperature, optimizing solar radiation absorption. The point of peak efficiency signifies an optimal configuration for effective energy conversion. However, beyond this point, further increases in convergence angle yield diminishing returns. Possible reasons include overheating and losses due to excessive sunlight concentration, shadows, or reflections within the collector, impacting effective collection area and efficiency. Higher convergence angles may alter airflow patterns, influencing heat transfer and collector efficiency. Material considerations, such as temperature limits, become crucial, as surpassing these limits can lead to reduced efficiency or damage. Engineers must carefully balance convergence angles to harness solar energy efficiently while avoiding detrimental effects on collector performance.

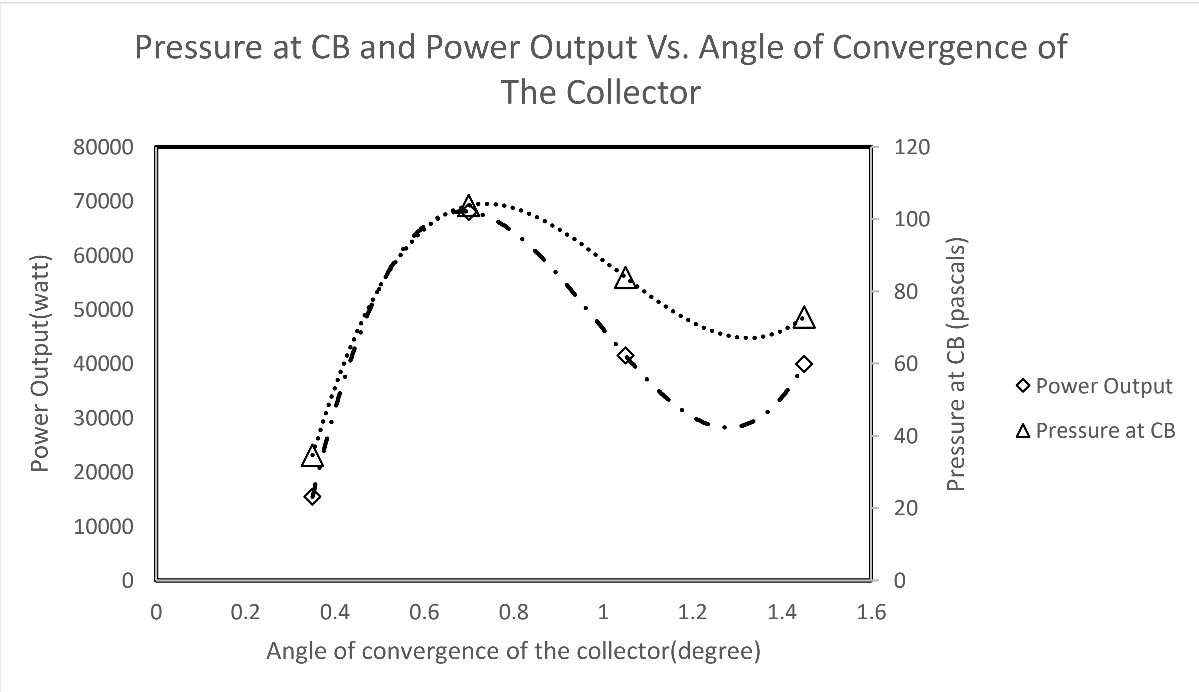

Figure 6- Pressure at CB and Power Output Vs. Angle of Convergence of The Collector

Figure 6 shows that the power output and CB pressure in a convergent chimney solar chimney power plant increase up to a certain point and then decrease before increasing again, suggests that there may be an optimal angle of convergence for the collector. Fig 6 outlines pivotal observations for solar chimney optimization. Initially, increasing the angle of convergence enhances power output and Collector Base (CB) pressure, driven by improved solar radiation collection and focused heat. The maximum point, where power output and CB pressure peak, signifies an optimal convergence angle. Beyond this point, further increases may induce negative effects like turbulence or recirculation, diminishing heat collection efficiency and reducing power output and CB pressure. However, subsequent adjustments within a certain range might mitigate these negative effects, potentially leading to a renewed increase in power output and CB pressure. Engineers must discern this delicate balance to optimize solar chimney performance, considering the nuanced impact of convergence angles on power generation and pressure dynamics.

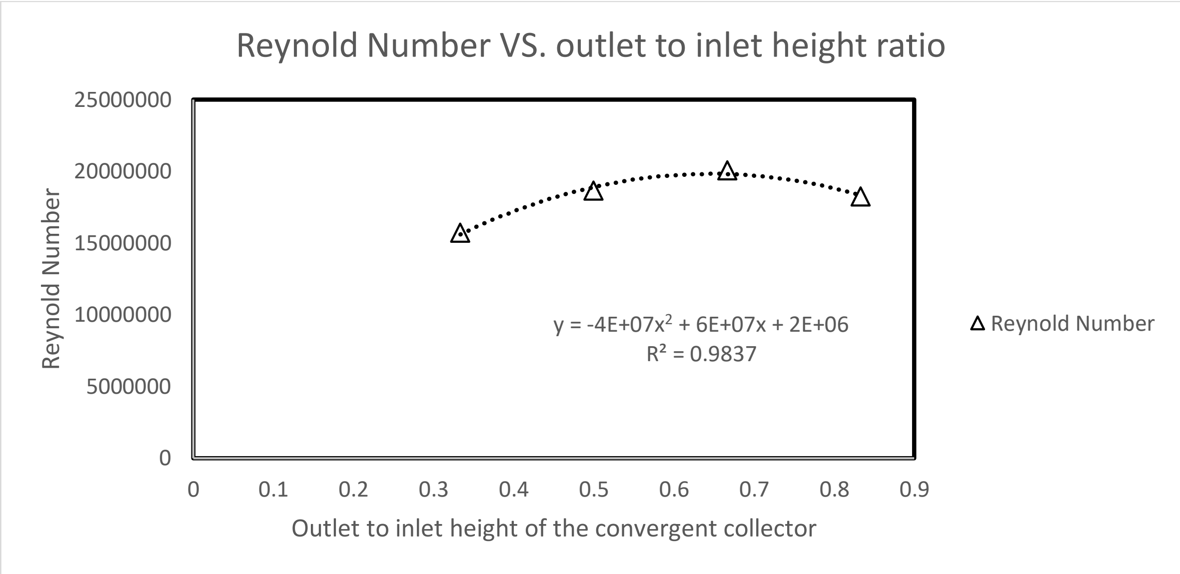

Figure 7- Reynold Number VS. outlet to inlet height ratio

Increasing the outlet-to-inlet height ratio of the convergent collector initially increases the Reynolds number but eventually results in a decrease which shown in fig 7 for a convergent chimney solar chimney power plant, could be influenced by several factors related to fluid dynamics. In Fig 7, an increase in outlet-to-inlet height ratio initially elevates the Reynolds number, indicating enhanced flow velocity within the collector. However, beyond a certain ratio, negative changes in flow dynamics, like turbulence or flow separation, cause a decline in the Reynolds number. This transition suggests a shift from an organized to a turbulent flow regime. To optimize convergent chimney solar chimney power plants, designers must carefully balance parameters, considering collector geometry, fluid properties, and flow dynamics to maintain efficient and predictable airflow within the system.

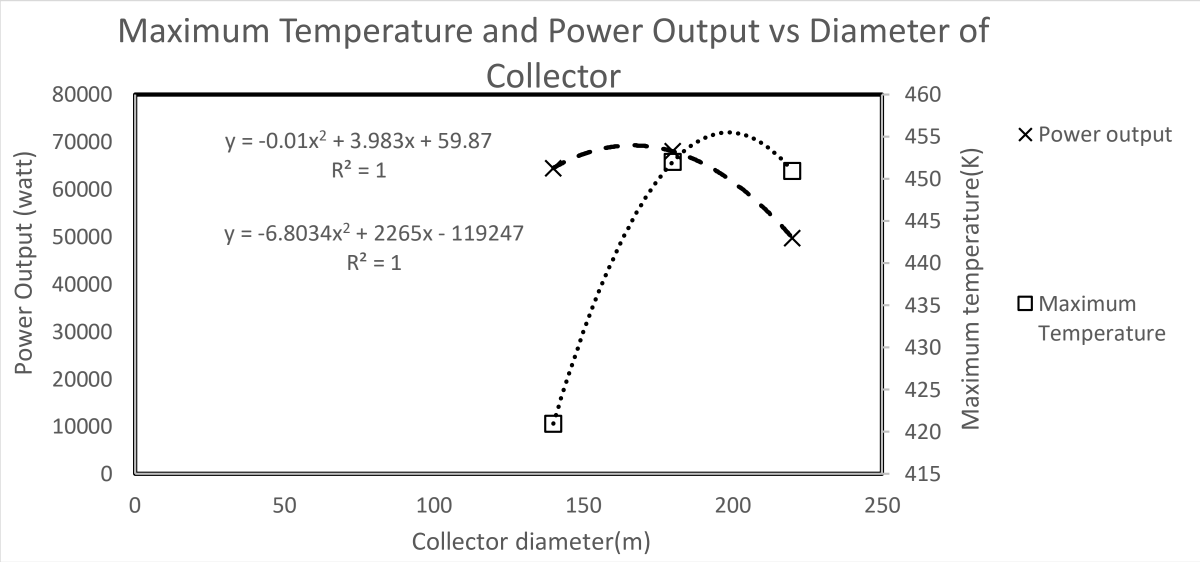

Figure 8- Maximum Temperature and Power Output vs Diameter of Collector

Increasing the collector base diameter initially increases power output and maximum temperature, but after a certain point, both declines, at a same height of the chimney but increase collector diameter which is shown in fig 8. In Fig 8, the collector base diameter's impact on solar chimney power plant performance is multifaceted. Initially, increasing the diameter enhances solar energy collection, raising temperatures, and augmenting power output by allowing more air flow into the collector. However, a critical point exists where further diameter increase disrupts flow dynamics, compromising heat transfer efficiency and diminishing power output. The interplay with chimney height is crucial; an imbalanced increase in diameter without corresponding height adjustment disrupts the buoyancy-driven airflow, reducing efficiency. Optimal design parameters must be considered, with a sweet spot where diameter complements chimney height for peak efficiency. Additionally, extreme temperatures resulting from larger diameters can harm collector materials, potentially leading to efficiency decline. A holistic approach, considering collector size, chimney height, and material properties, is essential for optimizing solar chimney power plant performance while mitigating potential drawbacks.

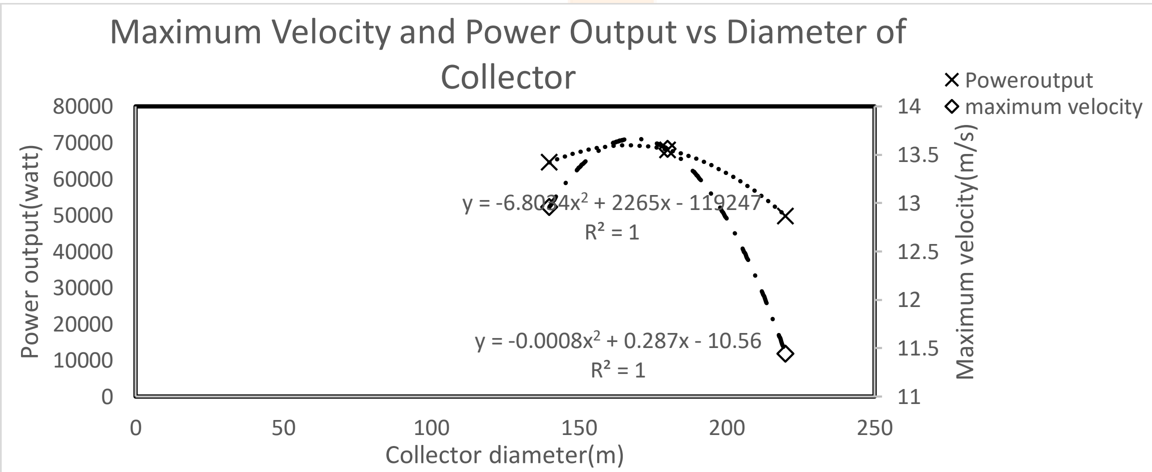

Figure 9- Maximum Velocity and Power Output vs Diameter of Collector

Collector base diameter when increases the power output and maximum velocity declines after a certain diameter but for the same chimney height with increased collector base diameter, it shows declining power and maximum velocity which shown in fig 9. Increasing the collector base diameter in a solar chimney augments the surface area exposed to sunlight, potentially boosting power output. However, several crucial factors must be considered for optimal design. While a larger collector captures more solar energy, the efficiency of heat collection may not increase proportionally; oversized collectors could lead to increased heat losses, reducing overall efficiency. The chimney height is critical, as an imbalanced increase in diameter may result in diminishing returns, causing lower air velocities. The complex relationship between collector size, chimney height, and flow dynamics entails careful design optimization. There's likely an optimal collector size for a given chimney height that maximizes power output; deviations may lead to diminishing returns or reduced performance. Balancing these factors is essential, as the relationship between collector base diameter, power output, and maximum velocity involves trade-offs, where excessive size may result in reduced performance due to efficiency losses and flow dynamics.

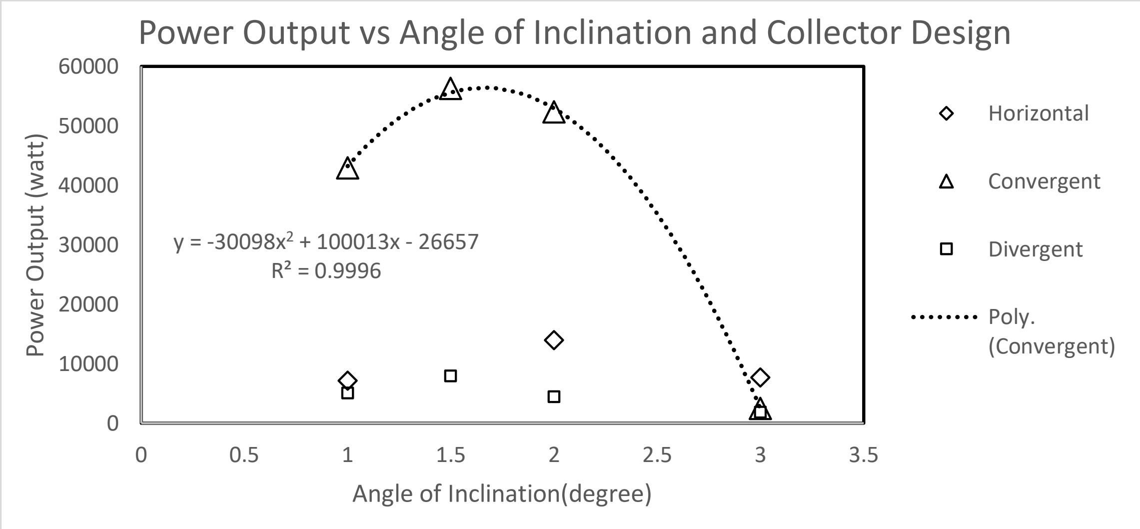

Figure 10- Power Output vs Angle of Inclination and Collector Design

A converging chimney Solar Chimney Power Plant (SCPP) with a 1.5-degree inclination angle and a convergent collector demonstrates superior power output compared to other inclination angles and collector types. The 1.5-degree convergence angle optimally balances solar exposure and natural convection. At this specific angle, the converging chimney design efficiently accelerates airflow, enhancing the temperature differential between the collector and chimney interior. The convergent collector complements this by maximizing heat absorption. This synergy results in increased power generation, surpassing the performance of other inclination angles and collector configurations. The 1.5-degree convergence angle represents a sweet spot in the design, leveraging the advantages of both converging chimney and collector configurations for optimal energy efficiency.

7.LOAD CAPACITY OF CHIMNEY

7.1 Dead Load Capacity:

To calculate the dead load of the basic and convergent chimney, we need to determine the weight of the chimney structure itself. The dead load is essentially the weight of the structure due to its own materials, without considering any additional loads like wind or snow.

First, we need to find the volume of the chimney:

$$V = \frac{1}{3}\pi h(R_1^2 + R_2^2 + R_1 \times R_2) \times \frac{L}{2} \qquad (15)$$

Where:

V is the volume of the frustum of the cone (chimney).

h is the height of the chimney.

R_1 is the radius of the base of the chimney.

R_2 is the radius of the top of the chimney.

L is the slant height of the frustum of the cone.

To find L, we can use the formula for the slant height of a frustum of a cone:

$$L = \sqrt{[h^2 + (R_1 - R_2)^2]} \qquad (16)$$

Now, to find the dead load, we need to multiply the volume by the density of the material used to construct the chimney.

$$\text{Dead Load} = V \times \text{Density} \tag{17}$$

7.2 Wind Load Capacity:

To calculate the wind load on the chimney with an average wind velocity of 1.6 km/H, we can use the formula for wind pressure and then multiply it by the projected area of the chimney.

The formula for wind pressure is given by:

$$P = 0.5 \times C_p \times \rho \times V^2 \tag{18}$$

Where:

P is the wind pressure.

C_P is the pressure coefficient (depends on the shape of the structure and the direction of the wind).

ρ is the air density.

V is the wind velocity.

To calculate the wind load, we need to multiply this pressure by the projected area of the chimney perpendicular to the direction of the wind.

First, we convert the wind velocity from km/h to m/s. Next, we need to calculate the pressure coefficient C_p for the chimney. For a cylindrical structure like a chimney, the pressure coefficient varies depending on the wind direction relative to the chimney's axis. A commonly used value for this situation is C_p = 0.6. For a conical shape situation c_p = 0.8.

The air density ρ typically ranges from 1.0 to 1.25 kg/m³. We'll use 1.2 kg/m³ as a standard value. Now, we calculate the wind pressure P.

Now, we need to find the projected area of the chimney perpendicular to the direction of the wind. Since the wind is acting horizontally, the projected area will be the cross-sectional area of the chimney:

$$A = \pi R^2 \tag{19}$$

Now, we can calculate the wind load W:

$$W = P \times A \tag{20}$$

7.3 Seismic Load Capacity:

To calculate the seismic load on the chimney, we'll again use the seismic coefficient method. Given the seismic coefficient, we can find the seismic load by multiplying it by the weight of the chimney.

Given, Seismic coefficient (S) = 10

$$W_s = S \times Dead\ Load \tag{21}$$

For example, 140m height, 10m diameter convergent chimney with a 1.5-degree convergence angle, calculate dead, wind, and seismic loads for maximum power output.

Table 4- Load Capacity Data:

Load Type	Basic Chimney	Convergent Chimney
Dead Load Capacity (kg)	1841150080.8	178306528.8

Wind Load Capacity (KN)	10.4457955732	11.1526539202
Seismic Load Capacity (kg)	18411500808	1783065288

The comparison between the basic and convergent chimneys reveals significant differences in load capacities which result are shown in table 4. The basic chimney exhibits notably higher dead and seismic loads, while the convergent chimney demonstrates slightly higher wind load capacity. These distinctions underscore the importance of considering chimney design and structural characteristics when assessing load-bearing capabilities, ensuring structural integrity and safety in varying environmental conditions.

8.CONCLUSION

In conclusion, the optimization of a Solar Chimney Power Plant (SCPP) involves a delicate balance of various parameters, including the inclination angle of the converging chimney and the design of the collector. The study explored inclination angles ranging from 1 to 3 degrees and different collector types, such as horizontal, convergent, and divergent. The findings highlight that a 1.5-degree inclination angle for the converging chimney, coupled with a convergent collector, consistently outperforms other configurations. This specific combination leads to higher collector efficiency, maximum temperature, convective boundary velocity, mass flow rate, and collector base pressure. The 1.5-degree convergence angle proves optimal, striking a balance between solar exposure and airflow control, ultimately enhancing the performance of the SCPP. However, as chimney height increases, the power output tends to decline beyond a certain point due to inefficiencies in convection. Factors such as increased construction costs, technical challenges, and environmental concerns further limit the economic viability and sustainability of extremely tall chimneys. The study also explores the impact of parameters like collector base diameter, outlet-to-inlet height ratio, and convergence angle on the SCPP's performance. Results indicate that careful optimization is necessary to avoid diminishing returns, especially in terms of collector size and chimney height. The relationship between these parameters is complex, requiring a nuanced understanding of fluid dynamics and thermodynamics to achieve optimal performance. Additionally, the study emphasizes the importance of considering local climate conditions, such as wind patterns and weather variations, in the design process. The performance of the SCPP is influenced by these external factors, and optimization strategies must account for site-specific conditions. In the pursuit of higher efficiency and power output, engineers must carefully balance various design parameters. Achieving the optimal convergence angle, collector type, and other relevant factors is essential for maximizing the economic viability and competitiveness of SCPPs in the realm of renewable energy generation. Furthermore, a comprehensive feasibility study and cost analysis specific to the project's location and requirements are imperative to determine the overall viability of a converging chimney design for a given SCPP. The study underscores the need for ongoing research and development efforts in the field of solar chimney technology. Technological advancements, especially in materials and construction techniques, may further reduce costs and enhance the performance of converging chimneys. Continuous innovation and optimization are essential for overcoming challenges and ensuring the sustained commercialization and improvement of this promising renewable energy technology. In summary, while a converging chimney design with a 1.5-degree inclination angle and a convergent collector demonstrates superior performance, the success of SCPPs relies on a holistic approach that considers site-specific conditions, economic viability, and ongoing advancements in technology. As the renewable energy landscape evolves, the optimal design for SCPPs may continue to evolve, making research and development crucial for the continued success and widespread adoption of this innovative solar power technology. The basic chimney exhibits significantly higher dead and seismic loads, indicating greater structural weight and seismic vulnerability. However, the convergent chimney shows slightly higher wind load, suggesting differences in aerodynamic behavior despite its lower dead and seismic loads.

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Declaration of competing interest. The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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