# computational and experimental investigation of a small scaled solar chimney power plant

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***Abstract*— The Solar Chimney Power Plant System (SCPPS), a pure thermal power plant consists of a collector to convert solar energy into thermal energy. A tall chimney where thermal energy is converted into kinetic energy and turbine to generate electric energy. In this study, Experimental and Computational investigations performed on the 1:62 scaled Solar Chimney Power Plant (SCPP) keeping Manzanares SCPP as Base model. A flat collector model with cylindrical chimney produces an average power output of 11.83W for consecutive three days of measurements. This small economical SCPP is viable to generate green electricity.**

***Keywords*— *Solar Chimney, CFD, Energy, Greenhouse effect***

## I. Introduction

Sunlight is the primary renewable energy resource on the planet earth. Generating Electricity from sunlight is useful to society as solar energy is never diminishing and abundantly available in large quantity. Solar Chimney Power Plant (SCPP) is a device that generates electric power from sunlight, where solar energy converted into thermal energy. It is a known fact that renewable energy solves the problem associated with conventional fuels used for power generation, as these sources are clean, free and inexhaustible. The solar chimney power plant operates on the principle that air gets heated up under a sizeable greenhouse-like collector; the warm air enters into the chimney due to buoyancy effect and runs the turbine at the base generating electricity. So far, there are many pilot plants established around the world for the last 25 years, and extensive research is taking place in this field, Schlaiah [1] first proposed the solar chimney tower in Manzanares, Spain, Table 1 presents the detailed specification of the plant. That plant was operated for almost eight years from the year 1982 because of the robust design and less operating costs; SCPP may be one of the viable devices for future green energy production. The operation of SCPP studied in Spain several studies were carried after to improve its thermal and aerodynamic efficiencies. In this aspect several prototypes are made and tested in an open environment, numerical simulations with CFD models have also been used to investigate the flow characteristics inside the chimney, collector. Hanna M.B et al. [2] designed a solar chimney power plant and conducted an experiment for four days and found that the chimney performance depends on the outside temperature. Mohammad o.Hamdan et al. [3] experimented 8m high solar chimney found that the airspeed peak is directly proportional to the temperature difference between collector inlet and ambient. Ehsan Shams et al. [4] have carried out the analysis in solar chimneys of different physical scales using CFD, the primary output of their work is the ratio of chimney height to collector radius influence actively the power out of the plant. A.A.El-Haroun [5] presented a mathematical model with 500m height, 3000m collector radius with an average power output of 18-19.6MW. He suggested that the power generation depends on the intensity of solar radiation. A. Koonsrisuk et al. [6] suggested that the air is more suitable than water to be the working fluid in a small scaled solar chimney CFD analysis. T.Mekhail et al. [7] developed a low-cost small SCPP by optimizing the chimney height on the performance of the plant when the chimney height from 6m to 20 m yields a maximum power output of 3W to 2 KW. M.Rafi Uddin Ahmed [8] carried out computational studies on the effect of collector inlet and outlet diameters on the performance of the plant. They suggested that the mass flow rate increases for variable collector inlet and outlet diameters. The Primary objectives of this study are

i) To get an insight into the physics of Solar Chimney Power plants

ii) To develop a simple, economical solar chimney to study the flow characteristics in it.

iii) To carry out computational analysis on the proposed SCPP.

## II. Mathematical Model

This work aims to develop a prototype which is aerodynamically efficient, i.e. investigating the performance of solar chimney without the turbine. We have conducted detailed CFD and Experimental Analysis of the prototype and compared the CFD results of Manzanares Plant and model developed by us. The air under the collector gets warmed up due to sunlight, the warm air is less dense than the ambient inducing the updraft effect into the chimney. The turbine located at the entrance of the chimney generates electricity. The power output of a solar tower [1] is

$$P = Q_{solar}\,\eta_{coll}\,\eta_{tower}\,\eta_{turbine} = Q_{solar}\,\eta_{plant} \quad (1)$$

Where the solar energy input $Q_{solar} = G\,h\,A_{coll}$ (2)

The chimney converts the heat flow produced by the collector into kinetic energy (convection current) and potential energy (pressure drop at the turbine). This density difference of the air due to the temperature rise in the collector works as a driving force. A pressure difference $\Delta p_{tot}$ produced between the tower base (collector outlet), and the ambient:

$$\Delta P_{total} = g \int (\rho_a - \rho_{tower})\, d_o. \quad (3)$$

Thus $\Delta P_{tot}$ increases with tower height. The pressure difference $\Delta p_{tot}$ is the sum of static and a dynamic component, hence,

$$\Delta P_{tot} = \Delta P_s + \Delta P_d \quad (4)$$

The static pressure difference is nill at the turbine, and the dynamic pressure corresponds to the kinetic energy of the airstream. The power $P_{tot}$ sustained in the flow and the efficiency of the tower may express as

$$P_{tot} = \Delta p_{tot}\, V_{tower,max}\, A_{coll} \quad (5)$$

$$\eta_{tower} = P_{tot} / Q_{solar} \quad (6)$$

Without placing a turbine, a maximum flow speed of 'V 'tower, max is achieved, and the whole pressure difference is used to move the air upwards, and also the pressure difference converted into kinetic energy.

$$P_{total} = 0.5\, m\, V^2_{tower,\,max} \quad (7)$$

Using the Boussinesq approximation (Unger, 1988), the maximum speed

$$V_{max} = [2gh\, \Delta T/T_o]^{0.5} \quad (8)$$

Hence, $\eta_{chimney} = gH/C_pT_o$ (9)

It is evident that to have an efficient tower the entire plant depends on the collector and chimney. A solar Chimney Power Plant ( SCPP) one with a flat collector and cylindrical tower is designed to produce approximately a power output of 8KW assuming the conditions such as the Temperature = 303K, density = 1.125kg/m$^3$ with a temperature rise of 5.5 K for 3.2 meter chimney height for a collector area of 13.2 m$^2$. The method of experimentation on the prototype plant is as follows, The tar road in Sri Venkateswara College of Engineering (SVCE) campus, Chennai, India is the place for considering the availability of sunlight and convenience of building the plant. The chimney radius was selected as 0.073m (7.3cm) considering the availability of chimney material in the local market. The ratio of collector diameter to chimney diameter called Diameter Ratio (DR).For building the prototype, we have chosen the DR as 25 and the scale factor as 1:62, where the scale factor is defined as a ratio of corresponding sides. For building the prototype, we have chosen the DR as 25 and the scale factor as 1:62, where the scale factor is defined as a ratio of corresponding sides.

$$\text{Scale factor} = \frac{\text{original collector length}}{\text{scaled collector length}}$$

| Parts | Manzanares Plant | Scaled dimension 1:62 Model |
|---|---|---|
| Chimney height | 194.6m | 3.2 m |
| Chimney radius | 5.09 m | 0.0855m |
| Collector radius | 122 m | 2.05 m |
| Collector height | 1.85 m | 0.264m |

Table 1: Specification of Manzanares plant and Experimental model

## III. Computational Analysis

The governing equations for mass, momentum, and energy are solved in ANSYS 18. The simulations were carried out using segregated implicit pressure based solver for steady state conditions. The governing differential steady incompressible flow equations for mass and momentum are solved. The turbulence is taken into account by the realizable K - ε model, with the inclusion of standard wall function for the near wall treatment. The second order upwind scheme has chosen for the solution scheme. The DISCRETE ORDINATES (DO) model [9] is selected as thermal radiation model, since it represents better the physicality of the radiation energy transfer phenomenon, compared to other commonly used models and due to an opportunity of applying the solar load directly to the DO model. The irradiations flux is applied directly to the semi-transparent walls as a boundary condition, and the radiative heat transfer is derived from the solution of the DO radiative transfer equation. "A pressure inlet" boundary condition for the air inlet at the periphery below the collector roof, and for the chimney outlet, an outflow condition is specified. The collector roof is considered as semi-transparent cover, to which the irradiation flux is applied directly, as a boundary condition. The solar radiation into the collector roof was changed in the range 400-1000W/m$^2$ based on actual weather condition. The Manzanares SCPP kept as the base model. The numerical simulations solved by using segregated implicit pressure based solver for steady state conditions. The steady incompressible flow differential equation for mass and momentum are solved. The buoyancy effect modeled with the Boussinesq approximation in the SCPP. The Modeling and meshing of the plant are carried out in ANSYS 18. The structured grid used for the analysis throughout the 2Dflow. Grid independence test carried out for 7000, 15000 and 30000 cells. The accuracy of results attained with 30000 cells. The Boundary conditions [11] appear in Table 2. Fig 1 and Fig 2 shows the SCPP model and the Meshed model. To validate the CFD simulation the temperature rise in the collector and the upwind velocity at the chimney inlet compared with the experimental data from the Manzanares prototype [10]. For the Manzanares prototype, the upwind velocity at the chimney base is 15 m/s and the temperature increase through the collector under no load conditions reaches 20 K. Table 3 shows the comparisons of the CFD result and the experimental data [10] for temperature and velocity of the Manzanares plant.

| **Location** | **Type** | **Description** |
|---|---|---|
| Collector | Wall | Mixed, semi-transparent |
| Ground or base | Wall | q = 0 W/m$^2$ , opaque |
| Chimney wall | Wall | q = 0 W/m$^2$ |
| Collector inlet | Pressure inlet | $\Delta p = 0$ |
| Chimney outlet | Pressure outlet | $\Delta p = 0$ |

Table 2: Boundary conditions

| **Source** | **Temperature increase** | **Updraft velocity** |
|---|---|---|
| Experimental data (Manzanares plant) [1] | 20 K | 15 m/s |
| CFD result | 19.1 K | 14 m/s |

Table 3 – comparisons of the CFD result and the experimental data [1]

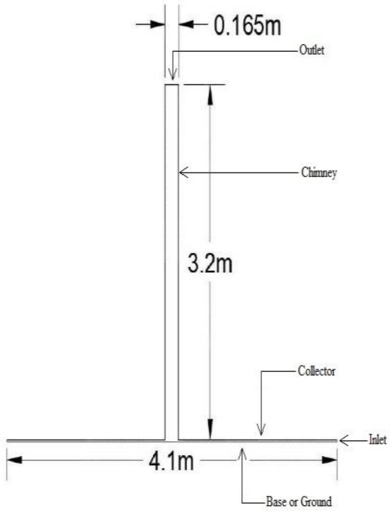


Fig 1: SCCP Model

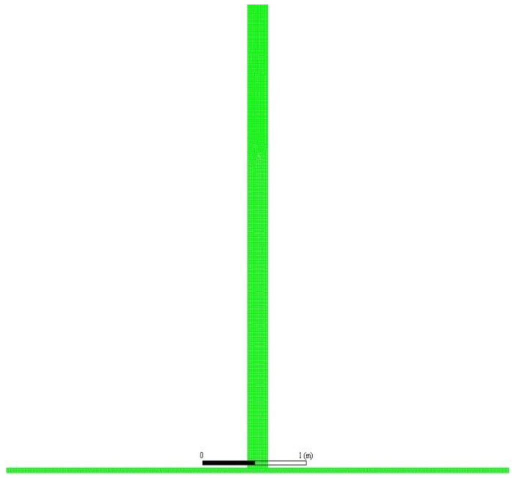

Fig 2: Meshed Model of SCCP

## IV. EXPERIMENTAL SETUP

Experimentation is carried out on the tar road in SVCE, Chennai, India, considering the availability of sunlight and convenience of building the plant. The chimney was made up of 5inch Poly Vinyl Pipe with 1.5m radius, and the transparent collector made of 250 microns Polythene cover and the divergent section from the chimney to the collector is of sheet metal. The entire structure rested on the steel bars. The base for holding the whole apparatus is placed in an Asphalt road since it absorbs more heat during the daytime. With the help of nut and bolts, the connecting rods are placed on the ground. These rods act as a support for the polyethylene sheets spread over them. The aluminum sheet is attached to the PVC pipe and is attached to the rest of the setup. The polyethylene sheets are used for radiation effect over the supporting rods.

Fig 3: Experiment Model

Hot Wire Anemometer of accuracy range measured the outside ambient temperature $T_0$ and the air velocity from ±3% to ±0.1% which measures velocity from 0.0 – 30.0m/s with a resolution of 0.001. The temperature at tower entrance Ti was measured at the same time by anemometer with an accuracy of ±1.0°C and a scale of 0.0 – 45.0. The air velocity at 0.2m from chimney entrance and 2.6m from chimney entrance are measured.

## V. RESULTS AND DISCUSSION

The study describes the working principle of SCPP based on the theoretical equations developed in the previous sections. The power output of the scope is a peak when the ambient temperature reaches a maximum value.

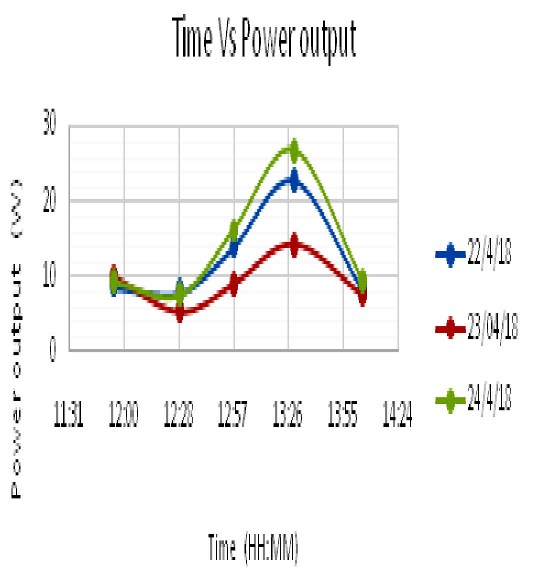


Fig 4: Plot of Time vs. Power output

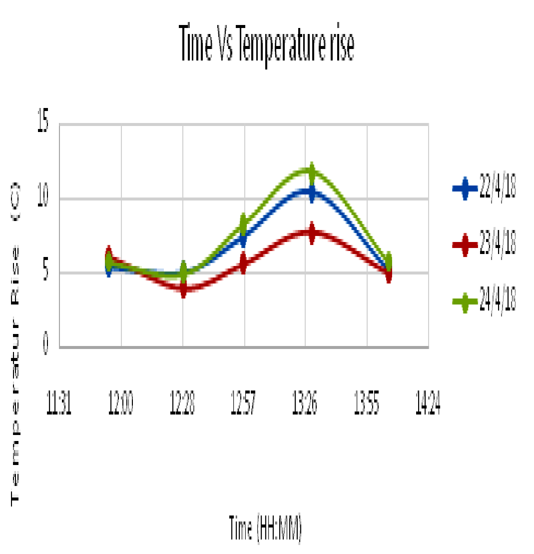


Fig 5: Plot of Time vs. Temperature Rise

Fig 5 shows that at the time of maximum temperature rise (i.e., the difference between the chimney inlet Temperature and ambient temperature) the power output is maximum. The efficiency also reaches its peak value at the time of maximum temperature Rise. The trend is correct on all three days which is evident from Fig 6.

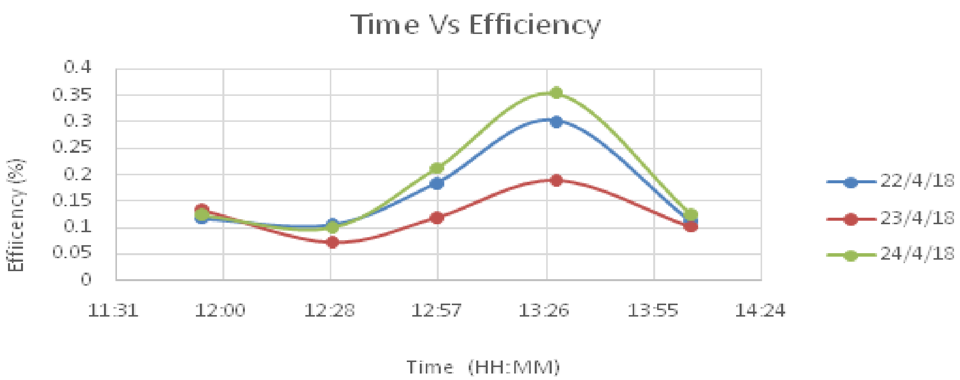


Fig 6: Plot of Time vs. the Efficiency of the Plant

The average power output of the plant reaches almost 14W which is quite higher than the design power output of 8W. Fig.7 shows the trend of average power output on all three days of measurement.

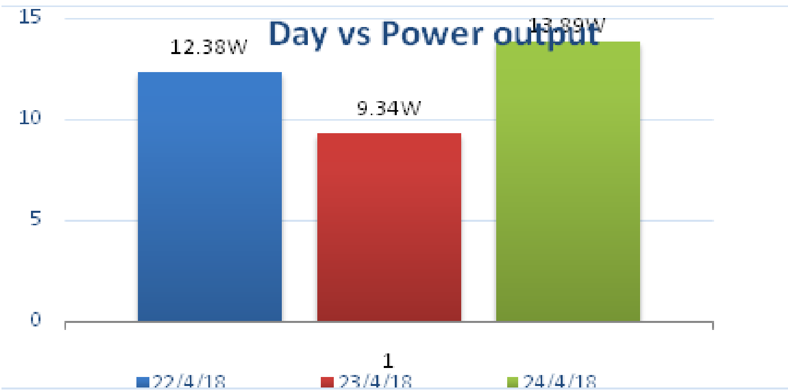


Fig 7: Plot of the Average power output of the plant

The updraft velocity is also maximum (Fig 8) at the time of peak temperature because of the density difference between the hot and ambient flow.

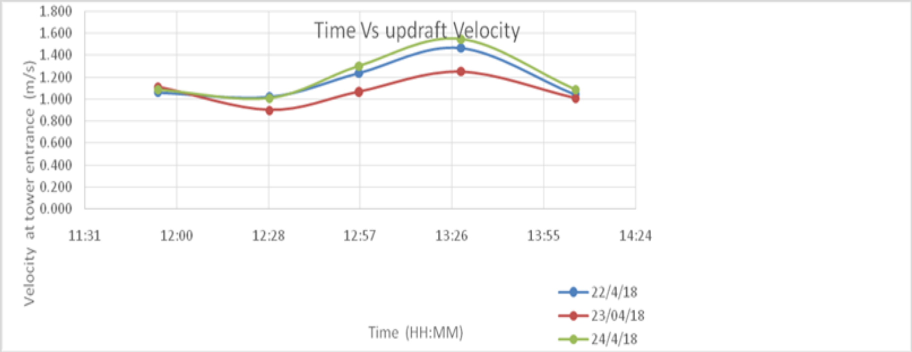

Fig 8: Plot of Time vs. Updraft Velocity

The curves explicit the fact that the power output of the SCPP is a peek when the temperature reaches maximum inside the Plant. Also due to the greenhouse effect, the hot air has risen upwards. The power output depends on the velocity at the entrance of chimney, pressure difference which is also peak approximately at the time when maximum sunlight radiation falls on the SCPP. Hence orientation of the plant is almost essential to have uninterrupted power generation during the daytime. CFD analysis done on the SCPP indicate the fact that the velocity shoots up near the chimney entry also the analysis in the collector also reveal that the velocity shoots up near the junction of collector and chimney. Fig 9 shows the velocity along with the chimney height, and Fig 10 shows the plot of velocity along with the collector. Fig 10 and Fig 11 depicts the velocity vector and velocity magnitude of the experimental SCPP respectively.

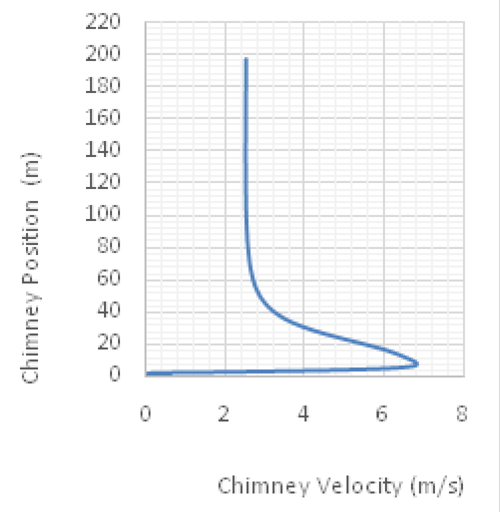

Fig 9: Plot of Velocity along the length of the chimney for Spanish Model

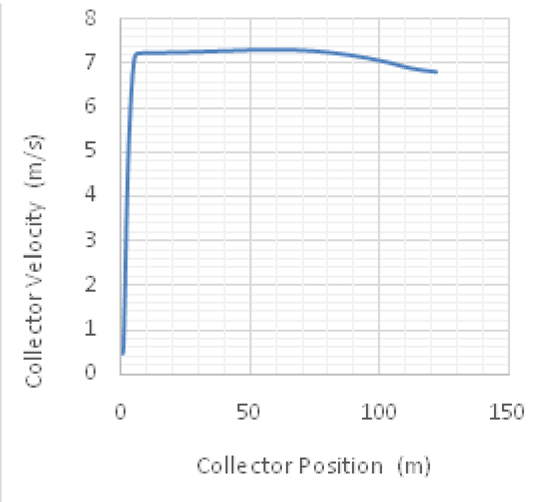

Fig 10: Plot of Velocity along with the collector for Spanish Model

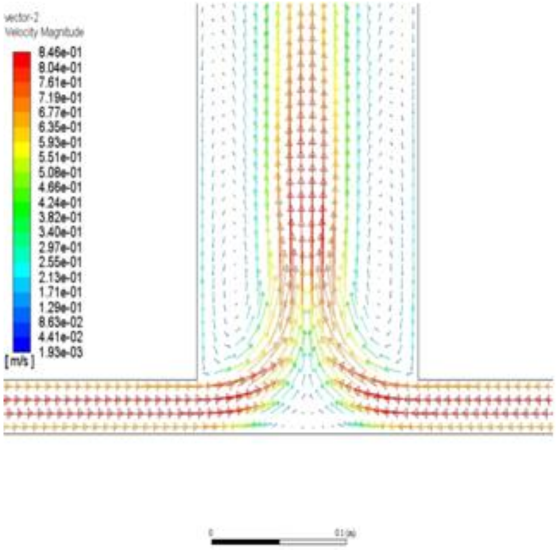

Fig 10: Velocity Vector of the Experimental Model

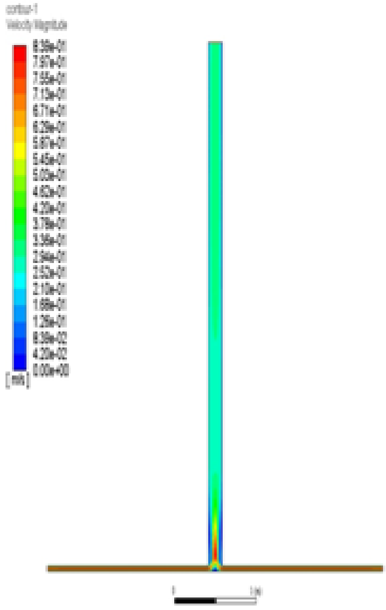

Fig 11: Velocity magnitude of the Experimental SCPP

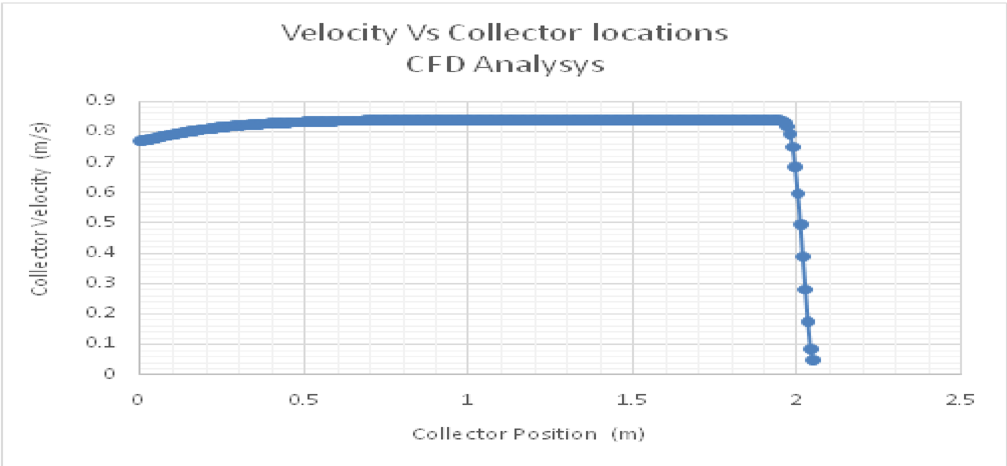


Fig 12: Plot of Velocity along with the collector (Experimental Model)

The Velocity along the chimney length from the base varies dramatically up to 40 in the Spanish Model validated through the CFD analysis (Fig 8); hence the measurement was taken at 0.23m from the base in the experimental study, for this model also the velocity almost matches the CFD results of the original prototype.

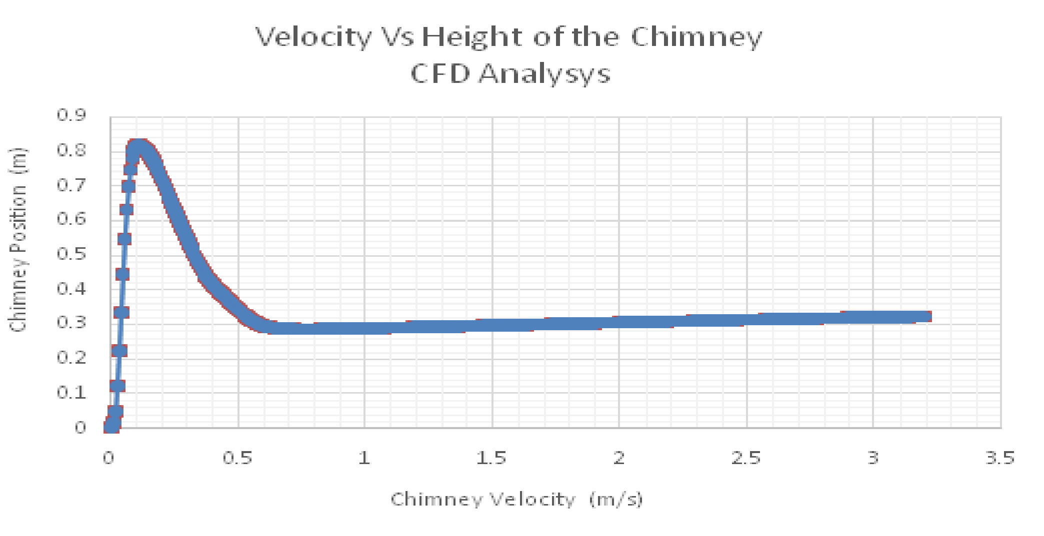


Fig 13: Plot of Velocity along with the chimney (Experimental Model)

Another important aspect of the experimentation part reveals the fact that even after the orientation of sun rays get declined, but the power output after its peak value did not fall steeply because of the greenhouse effect of the collector the heat inside the collector kept the air warm hence updraft effect continues. Therefore, by placing suitable thermal storage techniques, the SCPP can also able to run during night time also. The SCPP is kept on the asphalt road; thus, the Ground material also contributes to the greenhouse effect. Hence the SCPP may be placed on hilly regions, mountains and also it can be used as a drying tool for vegetables in places wherever been installed. From this discussion, we can conclude that SCPP is a most viable technique to generate green electricity even.

## VI. RESULTS AND DISCUSSION

The Solar Chimney Power plant is aimed to develop a power output of 8 W theoretically and constructed with actual measurements in the field for three consecutive days produces an average power output of 11.87W. Computational Analysis carried out on the model successfully. The Experimentation results obtained in this study are subjected to slight changes due to instrumental and human error. However, to understand the physics of the operating principle of an SCPP, this study is quite beneficial. Further research in experimentation and adopting different geometrical shapes to the chimney and collector to enhance the performance of the SCPP is required. Also, The turbine characteristics on the overall efficiency of the plant are to be studied in detail.

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