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Research Article

Performance evaluation of solar nozzle plant useful for electricity generation: A numerical analysis

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ABSTRACT

Passive solar electricity generation relies on natural heat transfer, avoiding the use of fans or pumps. To decrease overall cost, it is essential to discover some new techniques for optimizing the solar chimney plant's overall efficiency and capacity. The smoke jack devised by Leonardo da Vinci (1452-1519) has been quoted by many reviewers as the initial illustration of the principles of the solar chimney. The fundamental reason why it works is that it contains a venturi or nozzle. Thus, it is important to evaluate the performance of solar chimney plant using solar nozzles. Hence, this study numerically investigates the different configurations of solar chimney power plants (SCPP) with and without the use of solar nozzle design. The numerical analysis of the system has been done in ANSYS software with its latest available version (2022 R_1). The three different model configurations of SCPP were studied and found that using solar nozzle design; one can achieve increased air release velocity at the outlet, thus, enhancing overall system performance. This SCPP design offers a sustainable electricity generation solution for both urban and rural environments. The solar nozzle plant is primarily depending on three governing equations i.e. mass, momentum and energy conservation laws. The natural convection heat transfer phenomenon related to SCPP is the useful fundamental law of heat transfer. The solar chimney equation plays a pivotal role in deciding different design parameters such as chimney dimensions, and the air released velocities at various parts. With the help of appropriate formulae; the efficiency of the overall design can be calculated. Results show that with the help of solar nozzle design, one can improve air release velocity at the outlet by a significant amount to the conventional basic design of SCPP with no nozzle. This increase in air updraft velocity will have a considerable impact on the power output of the electricity generation plant when the turbine is fixed at the nozzle outlet region. The solar nozzle model 6 with 3 m of nozzle height shows an optimum increment of nearly 29 % than solar chimney model of 3 m height and with no nozzle used.

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INTRODUCTION

A solar tower power generating plant primarily uses solar energy for its operations. It is considered as a 'passive sustainable energy plant' that generates electricity. Passive solar technologies are those that do not use fans or pumps in the collection and usage of solar heat, instead, these technologies use the natural modes of heat transfer to distribute the thermal energy of solar gains among different spaces [1]. A passive, non-mechanical technique of producing energy is a solar chimney principle, often referred to as a thermal chimney [2]. Among the various forms of energy, solar energy is one that one receives from the Sun and is the prime energy source for solar updraft towers (SUT). This SUT uses natural convection heat transfer mechanisms. In this, any fluid motion is developed by the buoyant effect, which suggests the rise of warmer fluid and the fall of the cooler fluid (especially due to density differences) [3].Solar chimney power plants are privileged systems that can provide power output even in cloudy weather and during hours when there is no sun [4]. It can be further divided into two sub-categories i.e. internal or external flow depending upon the type of fluid flow. Use of clean energies such as solar, wind, geothermal, tidal, etc. for the generation of electrical power is helpful to reduce air pollution. Thus, it will surely save the environment on our planet earth. Wherever needed, the electricity can be produced by applying cleaner technologies to the power generation units. There is another method namely 'sustainable energy power generation techniques' which insists on the use of solar chimneys as shown in figure 1. It is use of the green energy options for generating electricity. This electricity will be helpful to both urban and rural developments. Figure 1 shows that the solar collector comprises a translucent cover to admit shorter wavelength solar radiation and retain long wavelength radiation that is emitted by the heated ground. Buoyancy-driven flow that is generated in the chimney is used to drive pressure-staged turbines installed at the chimney base for electric power generation [5].

In solar chimney sustainable power generation units, the solar radiations are fallen upon a large greenhouse-like structure available at the bottom. The collected solar radiations at the base region heat the surrounding air nearby collector portion, and thus creating an updraft within a tall chimney. The solar chimney is considered to be the plant's actual thermal engine [6]. During the morning time, sun radiations start falling on the absorber section and it slowly heats the absorber base. This will heat the air present within SCPP, thus creating an upward lift. If turbines are positioned in between the airflow; this lift will be beneficial to produce mechanical energy and then electricity by the help of generators. This upward lift drives turbine blades which are fixed nearer to the base of the solar chimney, thus generating electricity. The energy sources can be divided into two main categories i.e. Primary and secondary energy sources. The main energy consumption sources are fossils like coal, natural gases, etc., nuclear, and renewable options such as hydro-power, geothermal, solar, wind, etc. It is better to say electricity as secondary energy consumption source. The enhanced accumulation of CO_2 emission in developing countries poses a significant threat to the environment [7]. The SCPP uses solar energy which

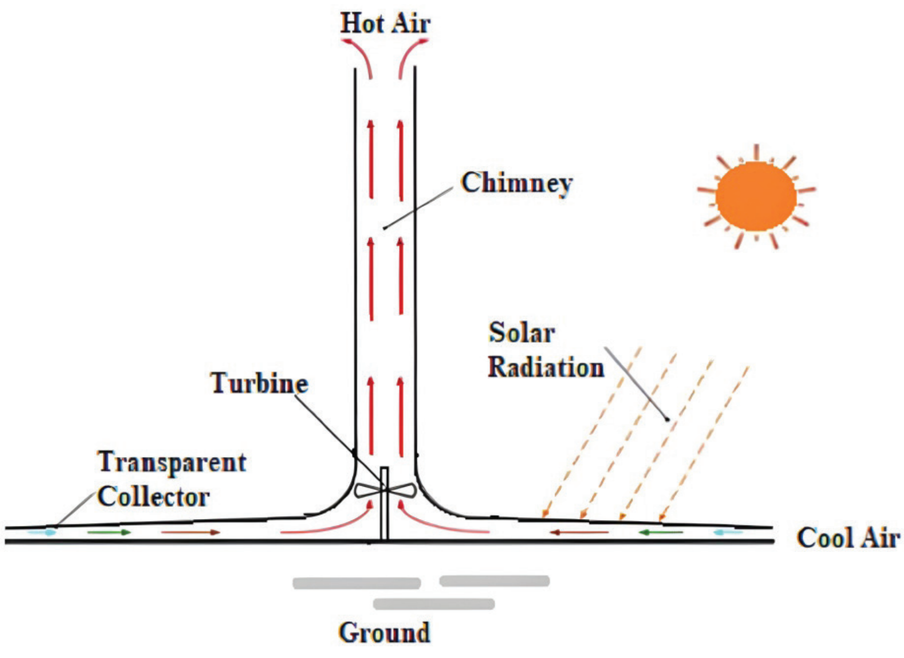


Figure 1. The basic structure of conventional SCPP.

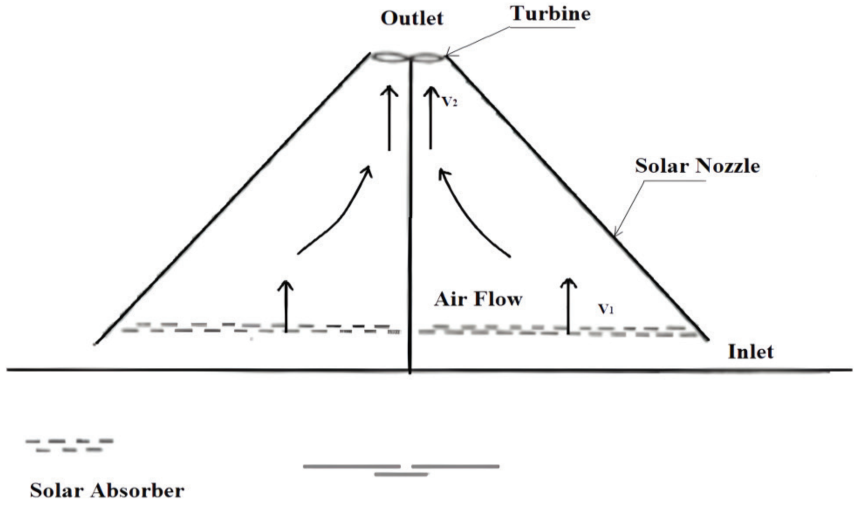


Figure 2. The Open ended conical shaped solar nozzle design. [From Williams [33], with permission from Global Warming Solutions.

is green energy option and has several advantages over conventional energy sources.

- It is available in abundant quantities free of cost in nature, completely pollution-free and thus an environmental friendly source of energy.
- It is known as one of the main renewable energy sources. It uses a clean and simple technology.
- It has a lower operational and maintenance cost, despite having higher construction costs. Fuel is not required in such a design. Here, no need to use fuels like coal, natural oil, etc., thus it's less polluting.

LITERATURE SURVEY

Al-Abadi et al. [8] have numerically investigated the combined solar-waste heat sources tower to increase power production. Here, a simulating software tool ANSYS FLUENT has been used. The main aim was to know the effects of waste energy of flue gases on the performance of solar towers. Hence, seven different models have been numerically tested having various chimney heights and diameters. Amongst these seven models, a circular shaped model with a two-ring burner was found to be the best option and thus recommended to use. The optimum of nearly 121.1 kW of power is produced. It delivered the highest thermal efficiency among other available choices. Cuce et al. [9] have conducted numerical analysis to know the appropriate values of the chimney as well as collector inclination angles for the pilot plant. The convergent and divergent chimneys have angles of -0.25° and + 0.25° respectively and it is found that the system notably performs if it has a slope for the chimney of nearly 0.6 ° and a diverging angle of about 1.5°. Marzouk [10] has used Aladdin artificial intelligence enhanced modeling tool to optimize Manzanares pilot plant design. By analyzing numerical results conducted for nine different locations in the world, results suggest that due to advancements in PV technology in recent years, the commercially built SUTPP that only generates electricity seems to have less chance of being established in the market. Tesfaye et al. [11] have done experimental and numerical analysis to increase the performance of the SCPP plant considering an optimum power output of around 30 kW. It is found that as one increase chimney height, it enhances power output up to a certain optimum height value, beyond which the effect is negligible. The pressure drop will result in significant energy losses along the chimney. It will start to overcome the energy rise because of the stack effect. The maximum chimney height is 45 m for a 0.2 m diameter, after that enhancing height results in negative of total pressure. Mirzamohammad et al. [12] have numerically modeled two different designs i.e. with and without using buried pipes. The impact of solar radiations and pressure variation in the turbine section by changing temperature in the computational domain is determined for both above cases. Due to the creation of obstacles in the airflow path after the rising pressure drop in the turbine, the air velocity in the chimney decreases subsequently. Singh et al. [13] have numerically investigated a high-capacity sustainable power unit that provides a cleaner and economically preferable option to conventional design. It is concluded that the geometrical features have a great impact on the performances of the SUTPP. The amount of solar radiations available and geometrical constraints mainly affect the efficiency and power output of the plant. Cuce et al. [14] have experimentally and numerically investigated the various effects of using solar absorbing materials like gravel or sand in a solar chimney power plant. It is found that using soil material as 'Sand', we can achieve a temperature rise of 67.3 K at a surrounding temperature of 290 K. Considering ambient temperature of

300 K, we can get a temperature rise of 64.8 K. Jiren et. al. [15] have performed a numerical study on an axisymmetric model of the prototype of solar chimney power generating plant using the different chimney heights and shapes which was built in Manzanares, Spain. By enhancing solar radiation intensity, the release velocity of air increases. It also enhances its temperature inside SCPP. By increasing the dimensions of the chimney and collector, one can raise the power output. Das et al. [16] have proposed a numerical investigation of SCPP. The aim was to evaluate the performance of SCPP using different collector roof designs. It is found that overall chimney efficiency increases by raisingits height and it decreases by raising collector roof angles. The different effect of collector roof angles on performance is evaluated. Various angles are: 20°, 25°, 30°, 35° and respective collector efficiencies are 87.2 %, 73.1 %, 60.5 %, and 51.8 %. Hoseini et al. [17] numerically found that an effective method for enhancing power output of SCPP is providing collector angles vs. horizon. The use of divergent collectors is more advisable than horizontal convergent collectors, as it produces higher velocity as well as mass flow rates. Jammei et al. [18] have numerically studied the different effects of varying geometrical parameters of SCPP. Researchers studied different tower convergence or diversion angles, and concave or convex wall forms with respective to the variation of velocity in the chimney. The various forms of chimney walls are simulated and studied with the aid of ANSYS FLUENT software**.** In basic design, the average air release velocity was found to be nearly 15 m/s; while it rises up to 23 m/s for the last model showing an enhancement of 49 %. Aurybi et al. [19] performed a numerical analysis on solar power plant. It was found that a hybrid SCPP design increases air velocity by 24 % and temperature by 9 %. Comparing numerical results of the conventional model with proposed model; the later produced more output power. Mekhail [20] performed numerical as well as experimental studies. Researcher used a small-scale SCPP plant which is installed in Aswan city for analysis purpose. With an increment in chimney's height by 14 m, there is an enhancement in the maximum theoretical power output of 3 W to 2 kW approximately. From the results obtained, it is clear that the bigger scaled model can produce theoretically an output that is 600 times more than a smaller one. Ming et al. [21] have numerically investigated SCPP. In this research work, some equipment is used to spread seawater droplets equally in the form of the surface. This is done when air flow is passed through the base of the chimney inside SCPP. With addition and humidification processes of the warm airflow, resulted in reduced air temperatures. Ayadi et al. [22] performed numerical as well as experimental analysis to check the performances of solar chimneys. Tests have been conducted in warm and tropical situations particularly of Kota, India. The impact of collector roof inclination is studied. Results indicate that using a negative roof angle, the thermodynamic efficiency of solar plants is enhanced. The air release velocity measured inside the solar chimney section is increased by 125 % by varying of angle by 2.5 °. Sundus et. al. [23] have performed experimental as well as numerical analysis. Results show that the selection of the correct ground material in the collector plays a prime role in increasing its performance. By raising the ground absorptivity, the ground temperature in the collector regions will be enhanced. The painted wooden material with a dark green color was the best choice among studied materials. Lal et al. [24] have performed experimental and numerical studies to find out the impact of various parameters like inlet temperature, chimney height, and solar radiation intensity on the system performance. Juo et al. [25] numerically studied the effects of turbine pressure drop, solar radiation, and ambient temperature on solar chimney system performance. Fasel et al. [26] have numerically demonstrated the impacts of using an unsteady RANS for SCPP. Pretorius [27] numerically evaluated the performances of larger-scaled SCPPs. Schlaich et al. [28] theoretically studied the SCPP plant. It was observed that constructing a solar tower of 1000 m height was difficult in previous times, but today, it could be constructed using recent advanced technologies. Caicedo et al. [29] studied radial turbine design for solar chimney power plants. Haaf et al. [30] experimentally (Part I) studied the solar chimney power generating plant installed at the Manzanares. The performances of solar collector and the converter were primarily influenced by local climatic conditions as well as site location. Soil characteristics like absorptive coefficient, coarseness etc. play a vital role in deciding how much amount of Sun's radiation energy could be converted into thermal energy. It was also observed that the upwind air release velocity for this pilot plant was 15 m/s. Haaf [31] experimentally investigated (Part II) the Manzanares pilot plant with a power output ranging to 55 kW. The system includes cost saving collector design along with a properly constructed energy converter unit inside the chimney of SCPP. Polyester film panels along with some soiled PVC panels were used achieving a greater transparency level.

Literature Gap and Motivation

After studying the above literatures on SCPP, we found some gaps and motivations for performing the research work. The current study explores the use of solar nozzles to enhance air release velocity and overall system performance in SCPP designs. The earliest work was done by Haaf et al. [30, 31] to develop a prototype design of solar chimney at Manzanares, Spain. Afterward, many researchers studied solar chimney plants to enhance its performance, but very few studied solar nozzle plant. Mainly Padki [32] studied a simple analytical model of solar nozzle plant and found that using chimney of varying inlet and outlet cross sectional area (i.e. converging or nozzle shaped chimney), could increase the overall system performance. However, no experimental or numerical studies were conducted. Williams [33, 34, 35] theoretically determined the performances of solar nozzle plants (Figure 2) with varying

Table 1. Optimum air velocities for different SCPP designs

Sr. No.	Researchers name, type of study, country, year	SCPP with/without nozzle	Chimney height, Absorber/base specifications etc.	Optimum air velocity (m/s)
1	Haaf W, Experimental Study, Manzanares Spain, 1983-84, [30, 31]	SCPP without nozzle	H= 194.6; $R_{coll.}$ = 122	15
2	Williams A, Theoretical study, UK, 2016 [33]	SCPP with nozzle	H= 5,$A_{Absorber}$= 25	36.80
3	Das et al., Numerical study, India, 2018 [21]	SCPP without nozzle	H= 5; $R_{coll.}$ = 0.3	1.85

dimensions and suggested researchers to further validate/disprove the ideas.

The objective of the current numerical study is to investigate various effects of using solar nozzle design compared to conventional SCPP design. Figure 2 shows the open-ended conical-shaped solar nozzle design with a solar absorber at its base. The smoke jack devised by Leonardo da Vinci (1452-1519) has been quoted in many reviews as the earliest illustration of principles of the solar chimney and if we look carefully at the smoke jack the key reason why it works is that it includes a venturi or nozzle [6]. Hence, it is important to evaluate the performance of SCPP using solar nozzles. Based on the literature review; some of the important designs of SCPP and their optimum air velocities are tabulated in Table 1.

METHODOLOGY

The design of SCPP will be based on various laws and stated as below:

a) Law of conservation of mass,

b) Law of conservation of momentum, and

c) Law of conservation of energy

Now, to calculate dimensions and other different parameters for SCPP, the following equations are used:

Maximum air velocity flowing in the tower (chimney) [28] is given by equation (1),

$$U_{tower,max} = \sqrt{\frac{2 \times g \times H_{tower \times \Delta T}}{T_O}} \tag{1}$$

The power output of the solar tower is stated as shown by equation (2),

$$P = Q_{Solar} \times n_{plant} \tag{2}$$

The tower (chimney) converts the heat flow produced by the collector into kinetic energy. The total pressure difference in N/m^2 is represented in equation (3):

$$\Delta P_{tot} = \Delta P_S + \Delta P_d \tag{3}$$

Considering static pressure difference equals zero, $\Delta P_S = 0$, then the total pressure difference will be as shown in equation (4):

$$\Delta P_{tot} = 0 + \Delta P_d = \Delta P_d \tag{4}$$

The total power output in watts is represented by equation (5),

$$P_{tot} = \Delta P_{tot} \times v_{towermax} \times A_{Collector} \tag{5}$$

$$n_{tower} = \frac{P_{tot}}{Q^{\cdot}} \tag{6}$$

To calculate the air velocity at the entrance height of the chimney (bottom or inlet of chimney section) inside SCPP, the following equation is used:

$$v_i^2 = \frac{2\,\Delta T_i\, g\, h_o}{T_a} \qquad [32](7)$$

Now, using the continuity equation, the air exit velocity (v_e) is given by equation (8):

$$v_e = v_i \times \frac{A_i}{A_e} \tag{8}$$

A_i: (Cross-sectional area at chimney entrance, m^2)

A_e:(Cross-sectional area at chimney exit, m^2)

At the chimney exit, the turbine is fixed and the air exit velocity can be represented as equation (9),

$$v_e^2 = 2 \times C_p \times \Delta T' \tag{9}$$

Solar insolation can be represented by following equation (10),

$$I = \rho \times v_i \times C_p \times \Delta T_i \tag{10}$$

Based on the above equations, we are going to design various components of our hybrid SCPP. The radiation Discrete Ordinates model (DO) is used for numerical analysis. According to this model, when radiation passes from one medium to another, the following equation (11) is used:

$$n_1 \times \lambda_1 = n_2 \times \lambda_2 \tag{11}$$

The solar irradiance method and fair weather conditions are used during the ANSYS-FLUENT analysis (Figure 3). For the fair weather conditions method following equations are applied and taken from the ASHRAE handbook and represented in equation 12:

$$E_{dn} = S_{etrn}\,S_{unprime} \tag{12}$$

The equation (13) for diffused solar irradiations on a vertical surface is stated below:

$$E_d = C\,Y\,E_{dn} \tag{13}$$

Here, 'C' is constant.

The equation (14) for diffuse solar irradiation for surfaces other than vertical surfaces is:

$$E_d = C\,E_{dn}\frac{(1+cos\epsilon)}{2} \tag{14}$$

There will be some ground reflected irradiations. Equation (15) represents such solar irradiations that fall on surface:

$$Er = E_{dn}(C + sin\beta)\rho_g\frac{(1-cos\epsilon)}{2} \tag{15}$$

Assumptions

- The density variation of air-fluid is a function of temperature and follows Boussinesq approximations.
- Fluid is 'air' and flow has a steady state. A turbulent model is used. The thermo-physical properties of air are assumed to be constant.
- The solar heat flux incident and absorbed in the absorber region is constant throughout the day. The sky is assumed to be clear and not cloudy during solar load calculations.

NUMERICAL ANALYSIS

The solar chimney power generating plant and solar nozzle plant are designed with the use of ANSYS-ICEM software (Figures 4, 5, and 6). We have performed numerical analysis with the help of the latest available version of ANSYS software. The following dimensions are considered while designing: dimensions of base = 3 m length and 3 m width, base height (inlet height) = 0.1 m, overall height (h) of the plant is varying based on different models (i.e. from 1 m to 7 m), the material of chimney and nozzle is polycarbonate, top dimensions of the nozzle or chimney = 0.5 m × 0.5 m. The squared cross-section (for chimney and nozzle) is considered with advantages of ease of manufacturing, and handling as well and the availability of workshop facilities. The model is designed in ICEM-ANSYS software (2022-R_1). The mesh is created in ICEM with body type hexagonal cells. The 3-dimensional RNG k-epsilon viscous turbulence model with steady-state conditions is considered for numerical analysis. The discrete ordinate radiation model is used for analysis purposes. The air density is defined by Boussinesq approximations and assumed to be 1.1455 Kg/m^3. The limitation of the study is that a flow of 'air' i.e. the fluid flowing inside the solar chimney; assumed to be incompressible flow, but in real situations, air is a compressible fluid. The various thermo-physical properties of materials are shown in Table 2. Comparing the dimensions mentioned in Table 1; height of chimney varies from 1 m to 7 m, while the base area is 9 m^2. Both SCPPs with and without nozzle designs are considered during numerical study.

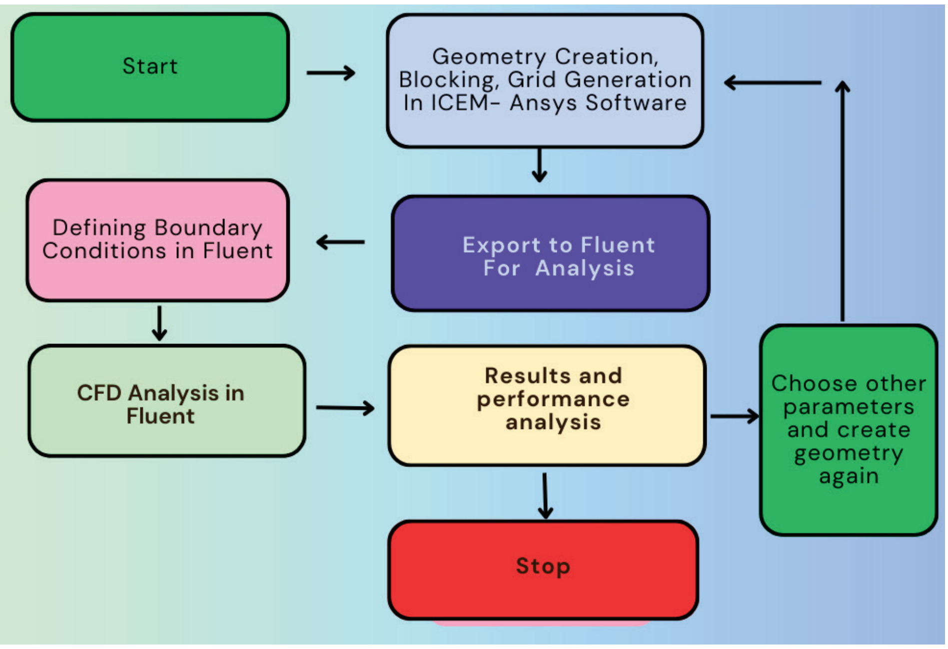


Figure 3. Flowchart of numerical analysis of solar nozzle plant.

The boundary conditions considered during analysis were: inlet conditions: gauge total pressure (Pa) = 0 Pa, total temperature (T) = 308 K, outlet conditions: gauge pressure = 0 Pa, backflow total temperature = 308 K, backflow turbulent intensity = 5%., the static pressure = 0 Pa. The multiphase model kept OFF and the viscous k-epsilon (2 equations) standard model was used. The enhanced wall treatment with a full buoyancy effect was used. The radiation discrete ordinates (DO) model was used considering solar load using a solar ray tracing model with solar calculator load conditions. The Rajkot city (India) location was used for solar loading conditions i.e. longitude 70.9 ° and latitude 22.27° with any summer day conditions. Wall conditions were: base thickness = 0.03 m, material = gravel, thermal boundary type = mixed, wall motion = stationary wall with no-slip conditions, solar nozzle: material= polycarbonate, radiation boundary type= semi- transparent. The following solver setting is used: pressure velocity coupling = SIMPLEC type, discretization scheme = second order and upwind. The location considered is 'Rajkot' (Gujarat, India) with direct solar irradiance = 810 W/m^2. The chimney material is 'polycarbonate'.

The radiation model is used with solar radiation 'ON' and the solar ray tracing model is applied for this location. The complete analysis in ANSYS-FLUENT is done for the above conditions and grid independence test results are shown in Figure 4. The grid independence test is performed and the most suitable grid size is selected for performing numerical analysis. The fine mesh type II (Figure 4) with nodes sized 38800 is selected for analysis.

Figure 5 shows a solar chimney plant designed in ICEM-ANSYS. It indicates a wire-frame view of SCPP, the designing of which is done using ANSYS software.

On the other hand, Figure 6 represents the solar nozzle plant in its three-dimensional view.

RESULTS AND DISCUSSION

Table 3 shows various models that are numerically analyzed to evaluate the performances of SCPP with and without a nozzle. There are a total of 8 models numerically studied. Out of these 8 models, 4 models are with solar chimney power generating plants (i.e. without nozzle) and the remaining 4 models are with solar nozzle power plants. All models were numerically studied with two different conditions i.e. fair weather as well as theoretically maximum solar irradiance conditions. Fair weather conditions have a sunshine factor of 0.9 while the theoretically

Table 2. Thermo-physical properties of materials [16]

	Thermo-physical properties ↓	(Part name) →	Nozzle	Absorber	Solar collector	Fluid
1	**Material name**		Polycarbonate	Gravel	Glass	Air
2	**Density (kg/m^3)**		1200	1840	2700	1.1455
3	**Sp. heat Cp (J/kgK)**		1170	840	840	1005

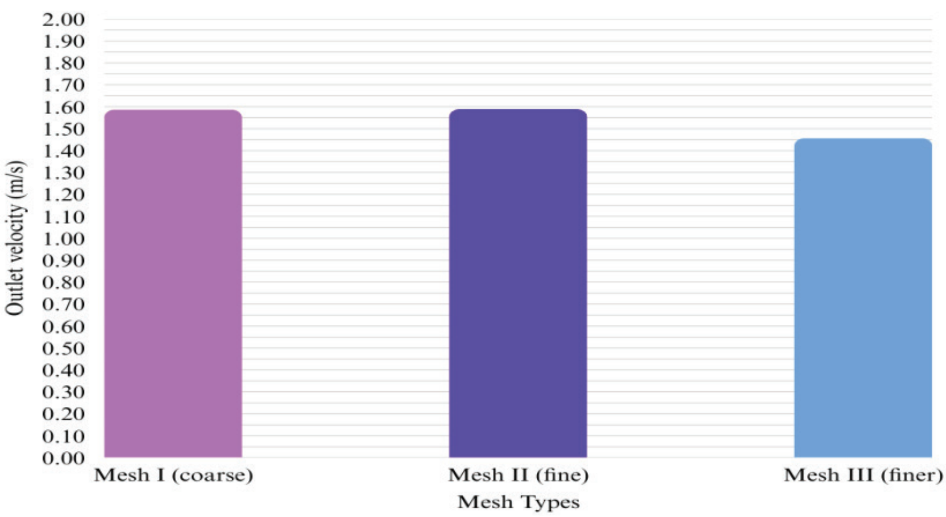


Figure 4. Mesh independence test.

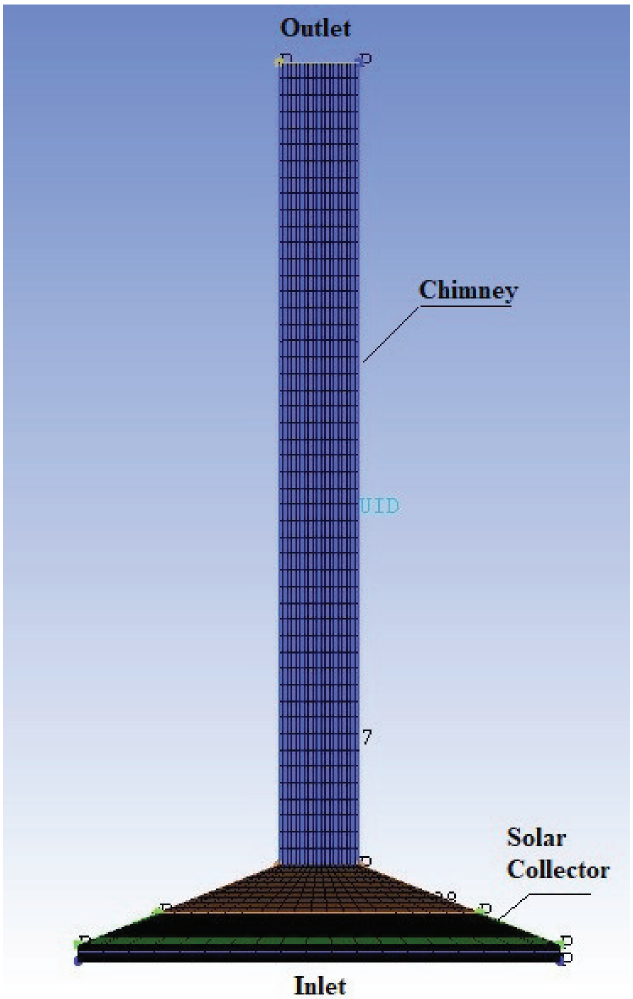


Figure 5. SCPP (designed in ANSYS-ICEM).

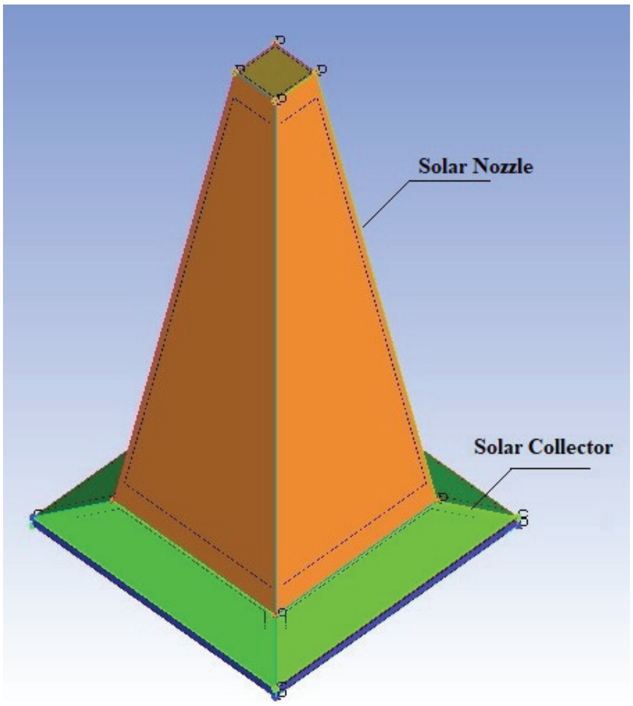


Figure 6. 3-D solar nozzle plant.

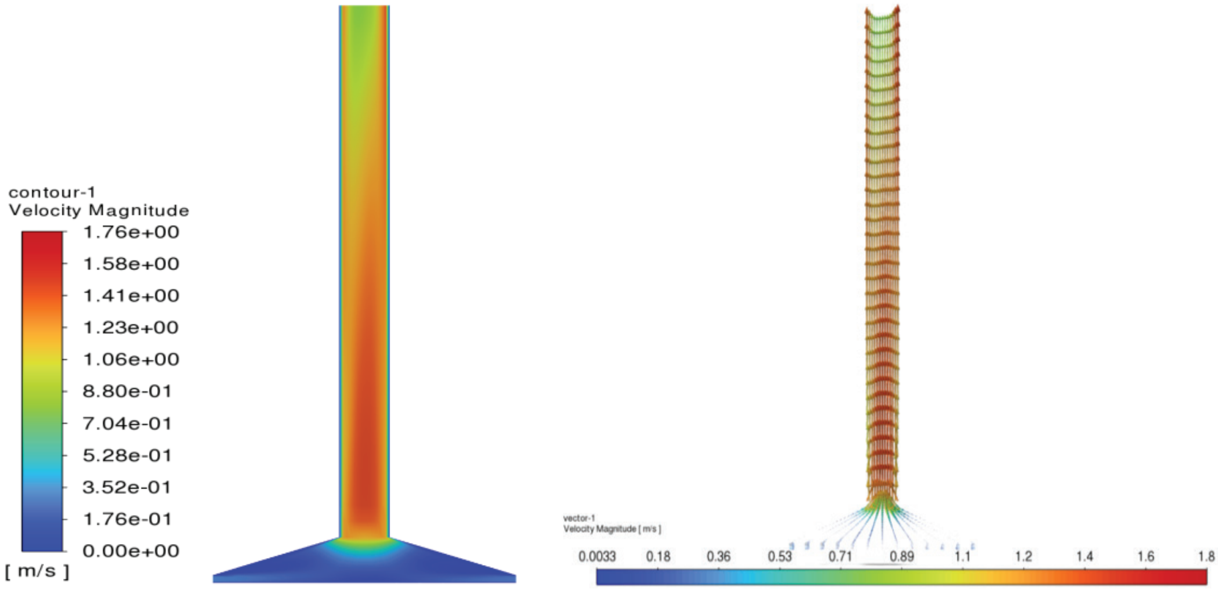
maximum method has a sunshine factor of 1. Figures 7 (a) and (b) show velocity contours and pathlines contours for model 1 (SCPP model with chimney height of 7 m) using fair weather conditions while Figure 9 (a) and Figure 9 (b) represent the same contours but using the maximum theoretical method in solar loading model. The numerical findings of all the above SCPP models are compared to the experimental results of Manzanares pilot plant which was located in Spain and studied by Haaf et al. in the year 1983. Figure 7 (a) shows the velocity contours, highlighting the maximum air velocity region near the chimney inlet and is indicated by reddish spots in Figures 7(a) and (b). Figure 8 shows the velocity magnitude and position plots for various sections in SCPP. The solar radiation falls on the absorber regions and is responsible for the rise in air temperature in the vicinity of the absorber. The heat transfer takes place due to the natural convection method. The static pressure of air is taken as zero at both inlet and outlet. At the center of the chimney, we get maximum velocity it reduces as we proceed towards the walls and is defined by the boundary layer theory.

Figure 9 (a) shows the velocity contours for a solar chimney power generation plant with a chimney height of 7 m. The cross-sectional region of the chimney is squared with a dimension of 0.5 m× 0.5 m. The maximum air velocity inside the chimney is 1.5 m/s using fair weather conditions (FWC). The solar ray tracing model is used with a sunshine factor of 0.9. Figure 9 shows the velocity contours, highlighting the optimum air velocity region near the chimney inlet. It is indicated by the reddish color in the figure. The power is generated by fixing turbines in this region. This can be converted into electricity using an electrical generator. The pathlines contour for the maximum theoretical method is represented in Figure 9 (b). During the numerical study, the gravel is considered as an absorbing material and is useful for maintaining air temperatures all over periods in the day i.e. during night times when solar radiations are minimal; absorbing materials help to gain stored thermal energy and thus continuous power generation is possible with these SCPP units.

Figure 10 (a) indicates the velocity contours, highlighting the maximum air release velocity at the nozzle outlet region and is denoted by reddish regions in Figure 10 (a) and Figure 10 (b). The numerical value for optimum velocity in the solar nozzle plant having a height of 7 m is nearly 1.75 m/s. The average total temperature at the nozzle outlet is 316.18 K. Figure 10 (b) shows pathlines for model 2. This is a design of a solar nozzle power generating plant

Table 3. Various models (model no.1 to 8) of SCPP and solar nozzle plant numerically designed using ANSYS and comparing with Manzanares pilot plant (model 9, Haaf et al. 1983)

Model No.	Absorber base (Material, dimensions etc.)	Chimney or nozzle (Material, dimensions etc.)	Numerical results with Fair Weather Conditions (FWC)	Numerical results with Theoretical Maximum Solar Irradiance Method (TM)	% Increase in air velocity (comparing SCPP with and without nozzle)
1	Material: Gravel Size: 3 m × 3 m (SCPP model with no nozzle)	Chimney material: Polycarbonate Size: Nozzle height = 7 m Top = 0.5 m × 0.5 m	Maximum air velocity inside chimney = 1.50 m/s Average total temp. at chimney outlet = 317.96 K	Maximum air velocity inside chimney = 1.77 m/s Average Total Temp. at Chimney Outlet = 321.54 K	0
2	Material: Gravel Size: 3 m × 3 m (Solar nozzle model)	Nozzle material: Polycarbonate Size: Nozzle height = 7 m Top = 0.5 m × 0.5 m	Maximum air velocity at nozzle outlet =1.75 m/s Average total temp. at outlet = 316.18 K	Maximum air velocity at nozzle outlet= 1.99 m/s Average total temp. at outlet = 318.44 K	16.66 (For FWC) 12.42 (For TM)
3	Material: Gravel Size: 3 m × 3 m (SCPP model with no nozzle used)	Chimney material: Polycarbonate Size: Chimney height = 5 m Squared cross section 0.5 m × 0.5 m size.	Maximum air velocity inside chimney = 1.32 m/s Average Total Temp. at Outlet = 317.63 K	Maximum air velocity inside chimney = 1.52 m/s Average total temp. at outlet = 319.69 K	0
4	Material: Gravel Size: 3 m × 3 m (Solar nozzle model)	Nozzle material: Polycarbonate Size: Nozzle height = 5 m Top = 0.5 m × 0.5 m	Maximum air velocity at nozzle outlet = 1.43 m/s Average total temp. at outlet = 315.20 K	Maximum air velocity at nozzle outlet= 1.61 m/s Average total temp. at outlet = 317.03 K	8.33 (For FWC) 5.92 (For TM)
5	Material: Gravel Size: 3 m × 3 m (SCPP model with no nozzle)	Chimney Material: Polycarbonate Size: Chimney height = 3 m Top = 0.5 m × 0.5 m	Maximum air velocity inside chimney = 0.92 m/s Average total temp. at outlet =314.51 K	Maximum air velocity inside chimney = 1.05 m/s Average total temp. at outlet = 316.67 K	0
6	Material: Gravel Size: 3 m × 3 m (Solar nozzle model)	Nozzle material: Polycarbonate Size: Nozzle height = 3 m Top = 0.5 m × 0.5 m	Maximum air velocity at nozzle outlet = 1.09 m/s Average total temp. at outlet = 314.01K	Maximum air velocity at nozzle outlet= 1.23 m/s Average total temp. at outlet = 315.44K	18.47 (For FWC) 17.14 (For TM)
7	Material: Gravel Size: 3 m × 3 m (SCPP model with no nozzle)	Chimney material: Polycarbonate Size: Chimney height = 1 m Top = 0.5 m × 0.5 m	Maximum air velocity inside chimney = 0.55 m/s Average total temp. at outlet = 311.84 K	Maximum air velocity inside chimney = 0.65 m/s Average total temp. at outlet = 313.29 K	0
8	Material: Gravel Size: 3 m × 3 m (Solar nozzle model)	Nozzle material: Polycarbonate Size: Nozzle height = 1 m Top = 0.5 m × 0.5 m	Maximum air velocity at nozzle outlet = 0.71 m/s, Average total temp. at outlet = 312.54 K	Maximum air velocity at nozzle outlet= 0.76 m/s Average total temp. at outlet = 313.21 K	29.09 (For FWC) 16.92 (For TM)
9	Manzanares pilot plant, Spain (Experimental study, W. Haaf et al 1983)	Tower height = 194.6 m, Tower radius = 5.08 m	The Air upwind velocity on release for pilot plant = 15 m/s	-	-



(a) (b)

Figure 7(a). Contours of velocity magnitude for SCPP model 1. **(b)** Pathlines for SCPP model 1.

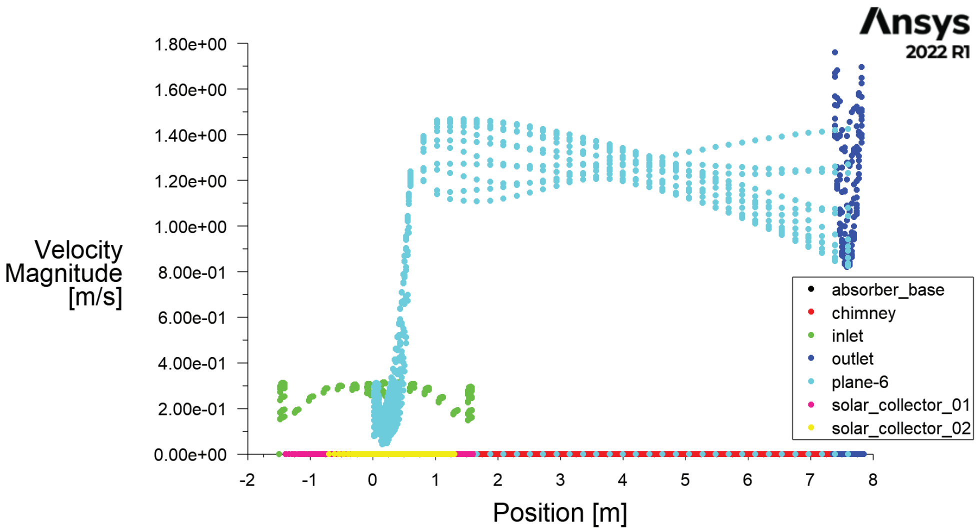
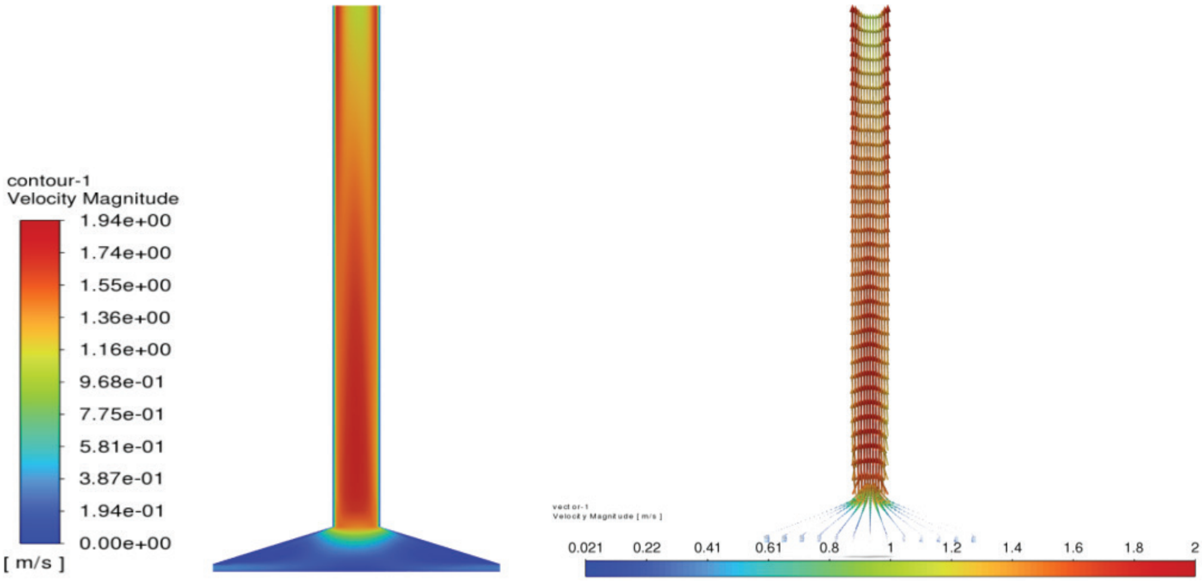


Figure 8. Velocity magnitude vs. position plot for model 1.

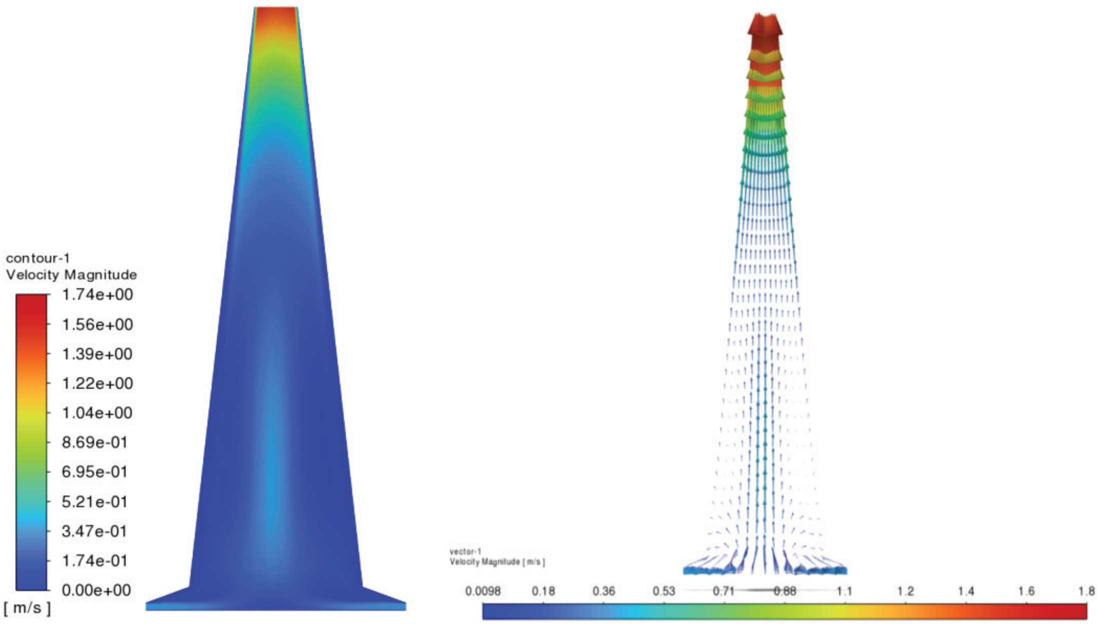
with a nozzle height of 7 m. Figure 10 (b) clearly indicates that, in this design, maximum air velocity is obtained at the nozzle outlet region. Above this nozzle outlet, a chimney is fixed to deliver air to the proper height to the surrounding atmosphere. Thus, the turbine is fixed in the regions of the nozzle outlet to gain maximum power output. Using equations (1) to (6) and considering dimensions for the model 3 (table 3) of SCPP with chimney height of 5 m, the various theoretical values for SCPP are: $U_{tower,max}$= 1.749 m/s, ΔP_d = 1.746 N/m^2, ΔP_{tot}= 1.746 N/m^2, P_{tot}= 27.49 W or 0.0274 kW, η (*Efficiency of chimney*)= 0.3665 %. The maximum air velocity inside the chimney (Numerical Value using solar irradiance theoretical maximum method) is 1.52 m/s for model 3 (Table 2). So, Theoretical and numerical values for maximum air velocity inside the chimney are close to each other.

Figure 11 (b) shows the velocity vs. position plot for a plane passing through SCPP's central axis and positioned in the vertical direction. The velocity, total pressure, incident radiation and heat flux contours for solar model 3are shown in Figures 11 (a),12 (a), 12 (b), 13 (a) and (b) respectively. Figure 14 suggests that the



(a) (b)

Figure 9(a). Velocity magnitude contour for SCPP model 1with TM method **(b)** Pathlines contour for model 1.

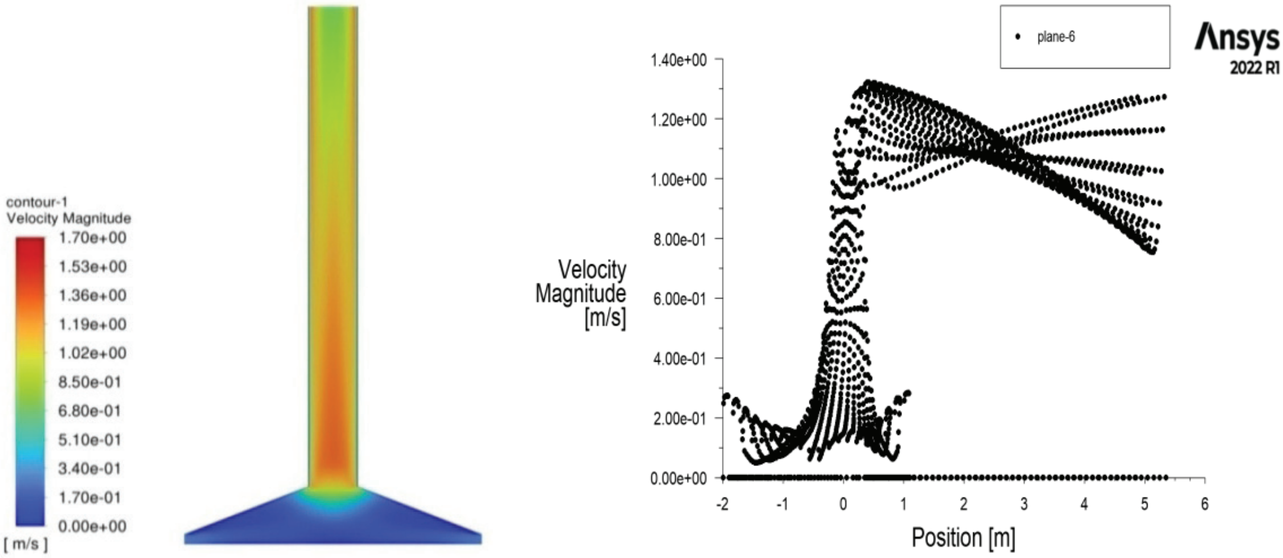


(a) (b)

Figure 10(a). Contours of velocity magnitude for solar nozzle model 2 **(b)** Pathlines contour for model 2.

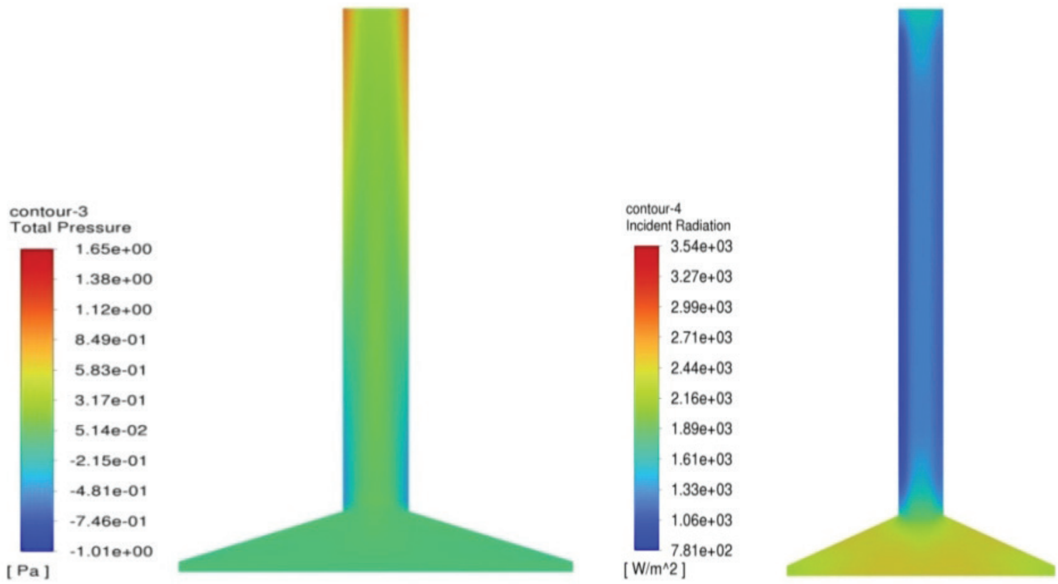
maximum air release velocity is found at the chimney inlet. The numerical value for optimum velocity inside the solar chimney plant having a height of 5 m is nearly 1.32 m/s. The average total temperature at the chimney outlet is 317.63 K.

Figure 12 (a) shows the total pressure contours for model 3 of a solar chimney power generating plant with a chimney height of 5 m. The total pressure is the sum of static pressure and dynamic pressure. The static pressure is assumed to be zero, so total pressure is nothing but the dynamic pressure of the air-fluid. Figure 12 (b) suggests the incident radiations that fall over SCPP and its effect is especially studied over the collector, chimney and absorber regions. These regions mainly contribute to the solar loading and thus resulting the rise of air temperature. Figure 13 (a) shows the solar heat flux contours for



(a) (b)

Figure 11(a). Velocity contours for SCPP- model 3 **(b)** Velocity and position graph for a central plane in model 3.

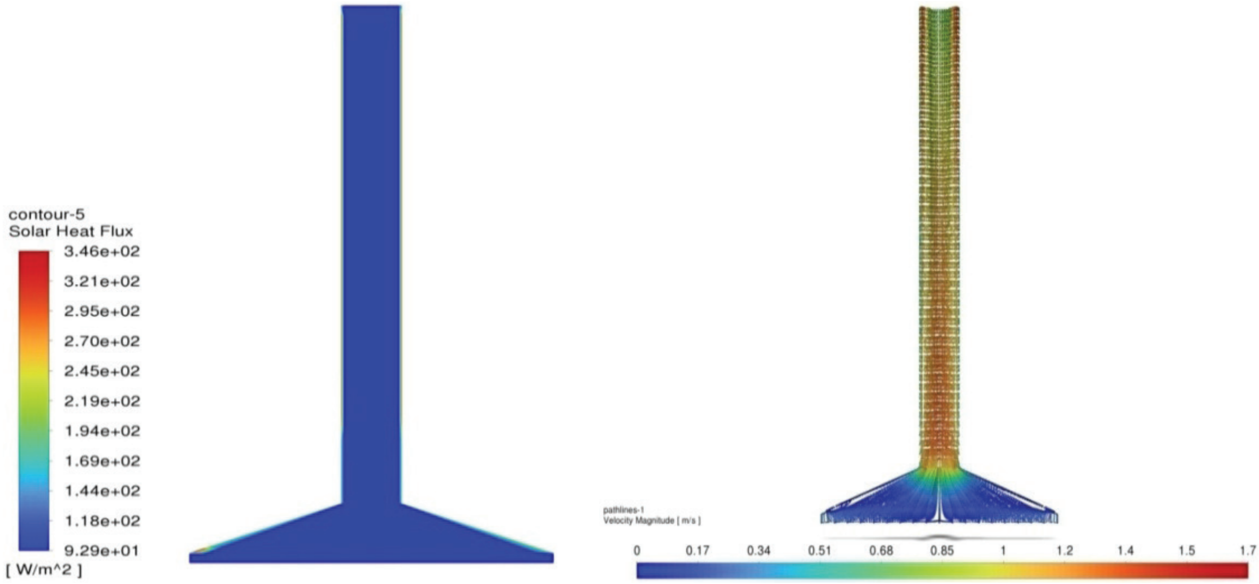


(a) (b)

Figure 12(a). Total pressure contours for SCPP- model 3**(b)** Incident radiations contour for model 3.

solar chimney plant model 3. In this numerical analysis, both collector and chimney regions participate in solar ray tracing and solar loading, to gain maximum of incident radiation energy. The numerical readings are taken considering a day in summer month at Rajkot (India) location and afternoon timings when solar radiations have higher availability and sky is clear. Figure 13 (b) shows pathlines for model 3. The following figures i.e. Figure 14 to Figure 23 show the rest of numerical models (as per Table 2) with different contours of velocity, solar heat flux and pathlines of velocities.

For model 4 with the solar nozzle of height 5 m, theoretical kinetic energy at the chimney outlet is 0.00785 kW and chimney efficiency is 0.25 % and is close to its numerical results (using equations 01 to 06). Figure 15 (b) suggests the solar heat flux for model 04 with a nozzle height of 5 m. The reddish as well as green spots are observed near the walls of an absorber and the chimney regions and they are clearly visible in Figure 15 (a), which indicates



(a) (b)

Figure 13(a). Solar heat flux contours for SCPP- model 3 **(b)** Pathlines contour for model 3.

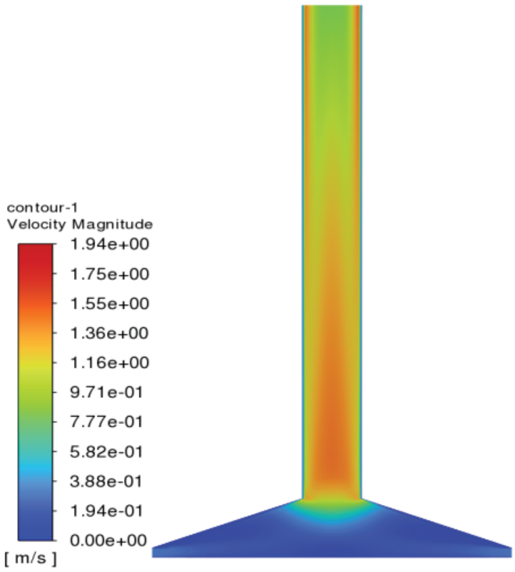


Figure 14. Velocity contours for SCPP- model 3 using theoretical maximum solar irradiance method.

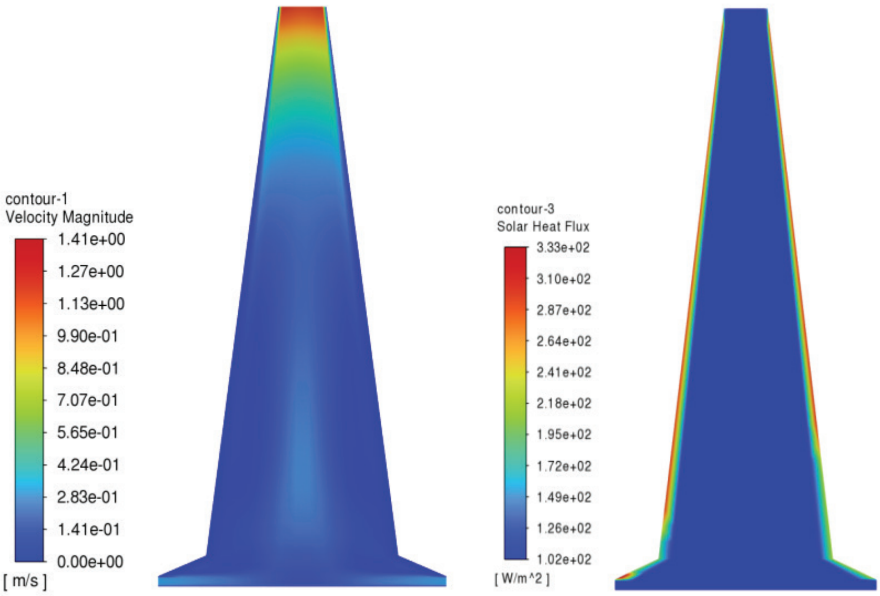
the absorbed solar radiations in those regions. When solar radiations fall on those surfaces, the air in the vicinity of it gains heat and rises up due to buoyancy effects. Thus, this results in maximum temperature at the nozzle outlet as per Figure 15(a).

Figure 16 (b) shows volumetric absorbed radiations in W/m^3 with respective positions in meters for a vertical plane passing through the central axis of SCPP. Figures 17 (a) and 17 (b) show model 5 of a solar chimney power generating plant with an overall height of the chimney is 3 m. The numerical value of maximum air velocity with fair weather conditions is 0.92 m/s. The numerical analysis suggests that with a theoretical maximum method (TM) the value is 1.05 m/s. It is close to its FWC value.

Figures 18 (a) and 18 (b) show velocity contours as well as pathlines contours for solar nozzle model 6 with a nozzle height of 3 m. The maximum air velocity at the nozzle outlet is1.09 m/s and the average total temperature is 314.01 K (calculated by numerical method with fair weather conditions).

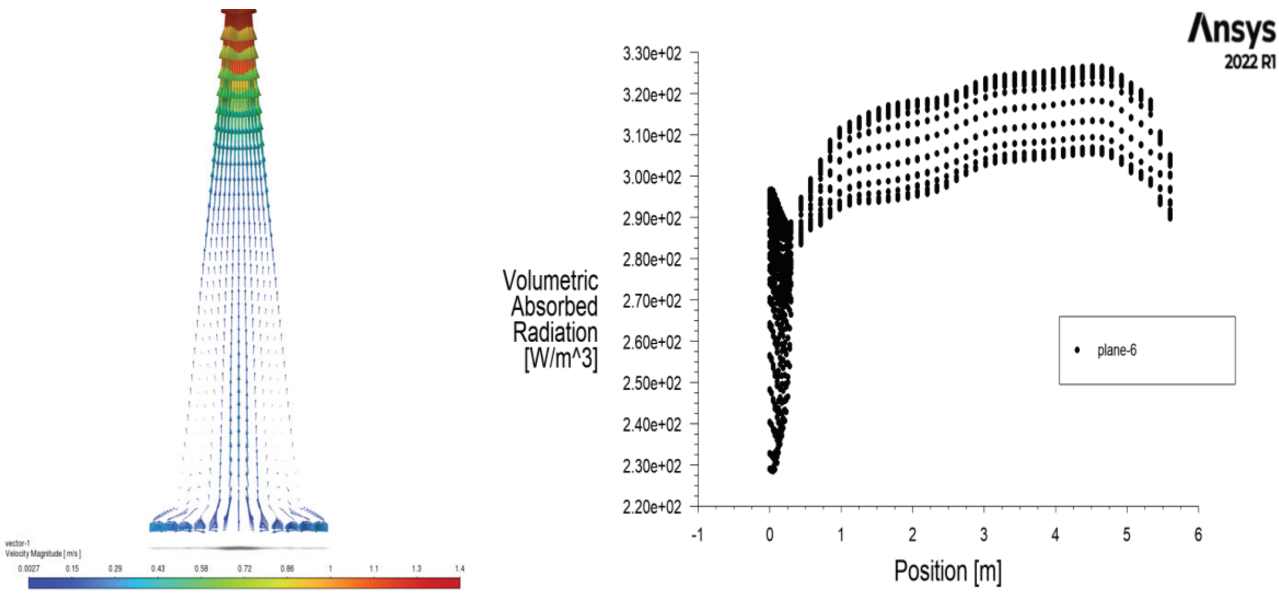
Amongst all studied models, model 7 and model 8 are with the least overall heights i.e. of 1 m height and the numerical results of an investigation are indicated in Figures 19 (a), 19 (b), 20 (a) and 20 (b). The maximum numerical value of air release velocity inside the chimney in Figure 18 (a) is nearly 0.55 m/s. The average total temperature at the chimney outlet is nearly 311 K. Figure 18 (b) indicates the pathlines of the air flow inside the SCPP design. The air enters from the bottom regions inside the SCPP (i.e. from the inlet section) and it receives the solar heat at the collector regions (due to incident solar radiations). Because of the increase in its temperature, it rises upward into the chimney, thus creating an upward thrust. This upward thrust is then converted into power output when air falls over the turbine blades. Thus, we can generate electricity from the SCPP.

From Figure 20 (a), it's clear that the maximum velocity of air-fluid is obtained at the nozzle outlet regions for solar nozzle power plant with a height of nozzle equal to one meter. The air movement increases near the nozzle outlet



(a) (b)

Figure 15(a). Velocity contour for solar nozzle model 4 **(b)** solar heat flux contours for model 4.

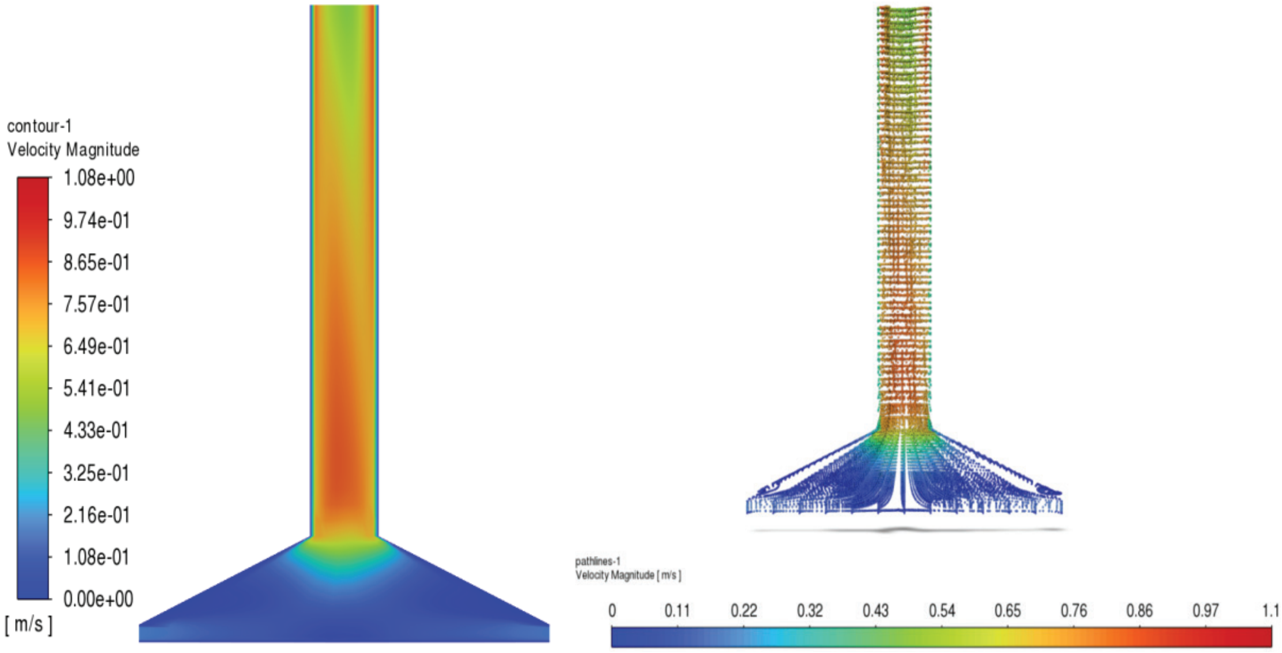


(a) (b)

Figure 16(a). Pathlines contours of velocity magnitude for solar nozzle model 4 **(b)** Volumetric absorbed radiation vs. position contours for model 4.

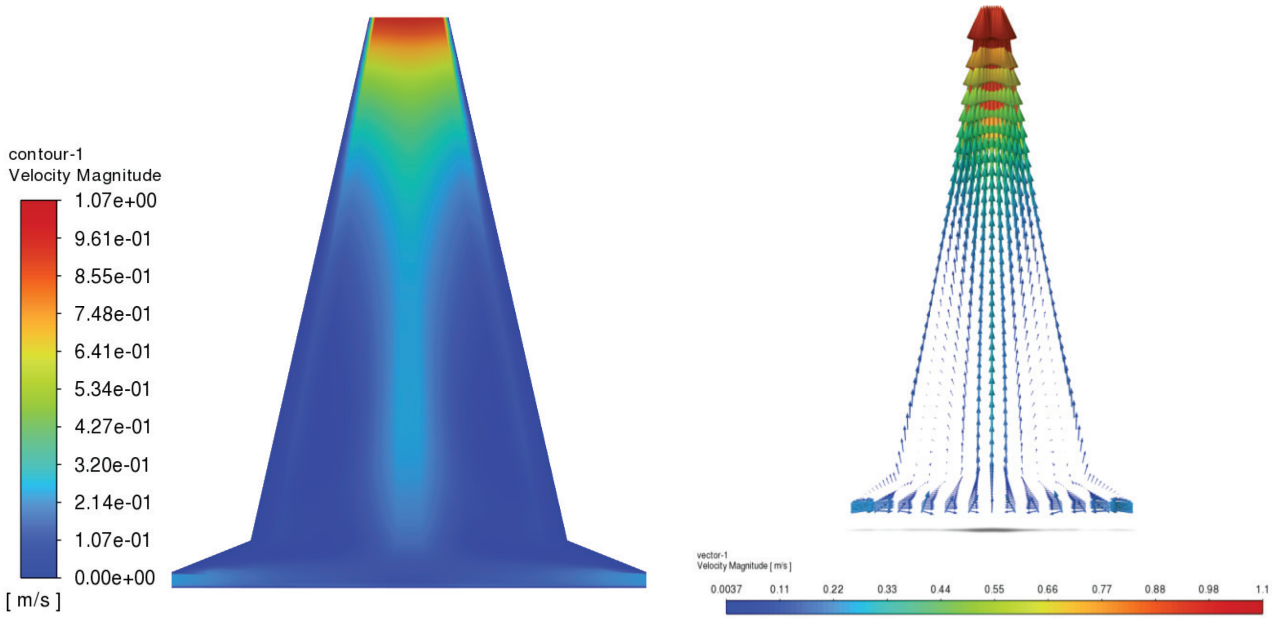
as indicated in Figure 20 (b), as air is passed through this converging shape i.e. nozzle shape. The turbulent model is used for numerical analysis. Figure 21 shows the velocity and position plot for model 8. Figure 20 and 21 show chimney heights and maximum air velocity comparison for fair weather and theoretical maximum conditions for various mentioned models in Table 2.

Figure 22 and 23 shows that as chimney height increases, the corresponding values of maximum air velocities also increase. For a given overall height of the plant, the maximum value of air velocity in m/s is higher



(a) (b)

Figure 17(a). Velocity contours for SCPP- model 5 **(b)** Pathlines contours for SCPP model 5.

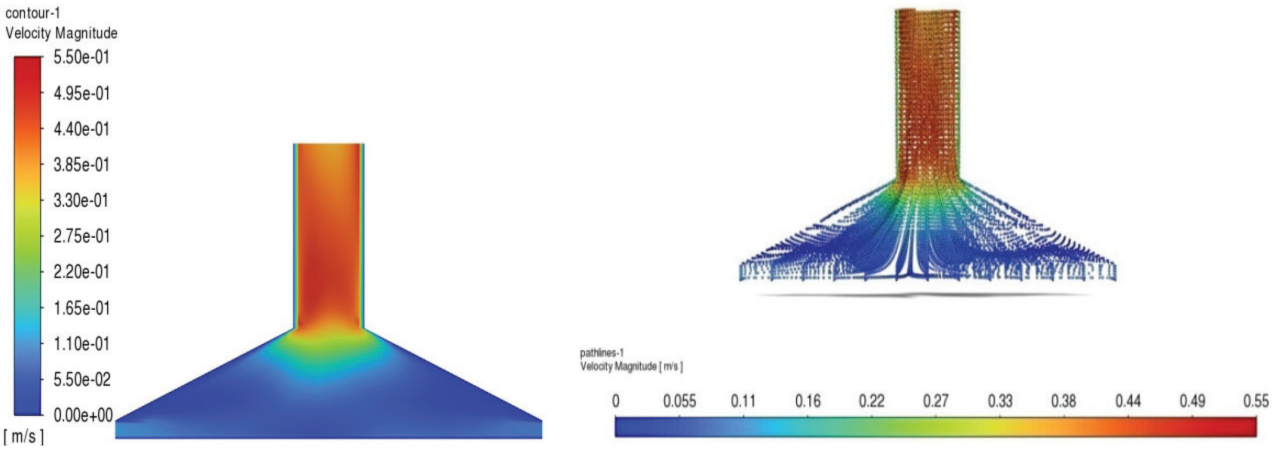


(a) (b)

Figure 18 (a). Velocity contours for solar nozzle- model 6 **(b)** Pathlines contours for SCPP model 6.

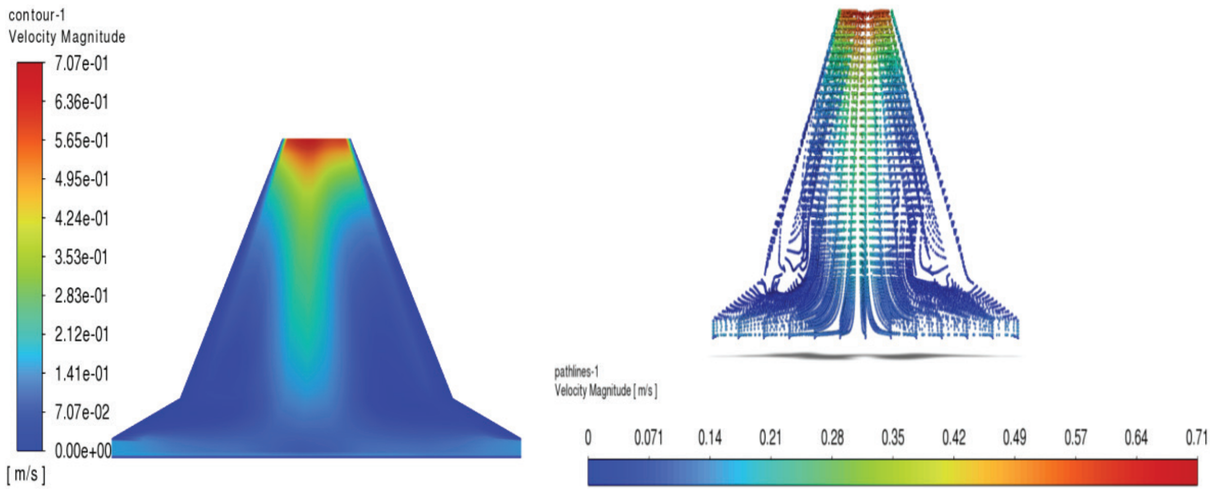
for solar nozzle plant than that of SCPP with no nozzle plant.

Figure 23 suggests that as chimney height (in m) increases, the corresponding values of maximum air velocities (in m/s) also rise. For a given overall height, the value of air velocity in m/s is higher for solar nozzle plant with theoretically maximum method (TM) than that of fair weather conditions (FWC). Figures 24 and 25 show that as chimney height increases, the average temperature of air at outlet also rises (for both plants i.e. SCPP with and without nozzle).



(a) (b)

Figure 19 (a). Contour of velocity magnitude for SCPP model 7**(b)** Pathlines contour of velocity magnitude for SCPP model 7.



(a) (b)

Figure 20(a). Contour of velocity magnitude for solar nozzle model 8 **(b)** Pathlines contour of velocity magnitude for solar nozzle model 8.

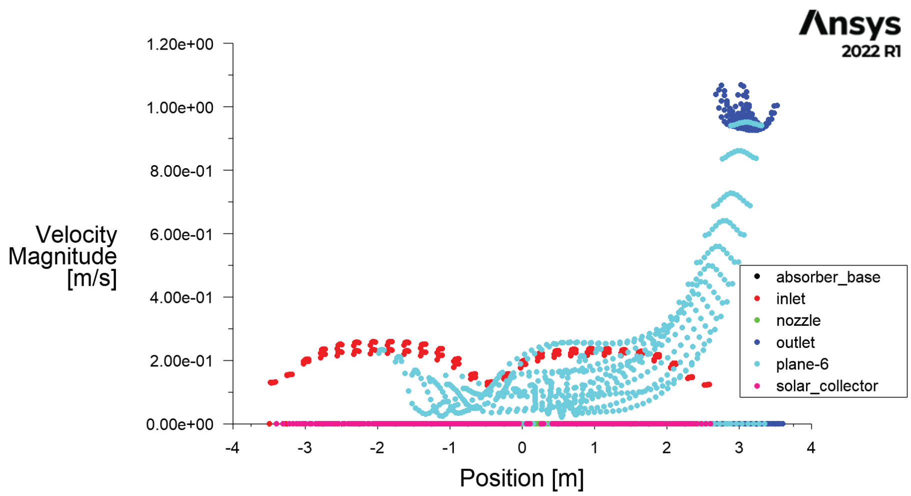


Figure 21. Velocity magnitude vs. position plot for solar nozzle plant - model 8.

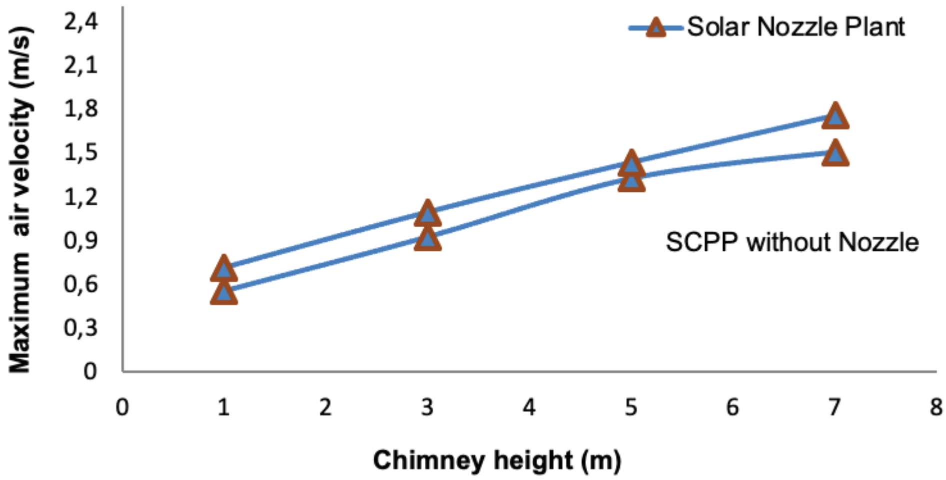


Figure 22. Comparison of chimney height with max. air velocity (FWC) for SCPP with and without nozzle.

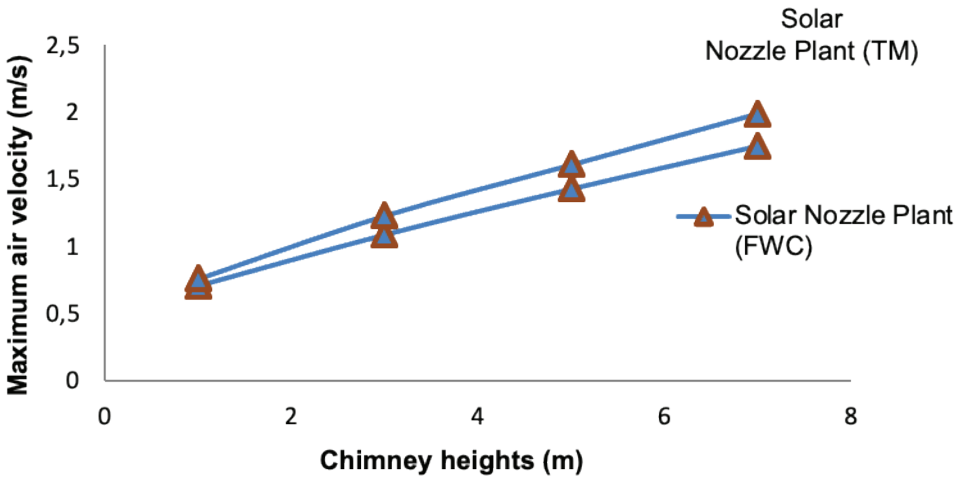


Figure 23. Comparison of chimney height with max. air velocity with FWC and TM for solar plant with nozzle.

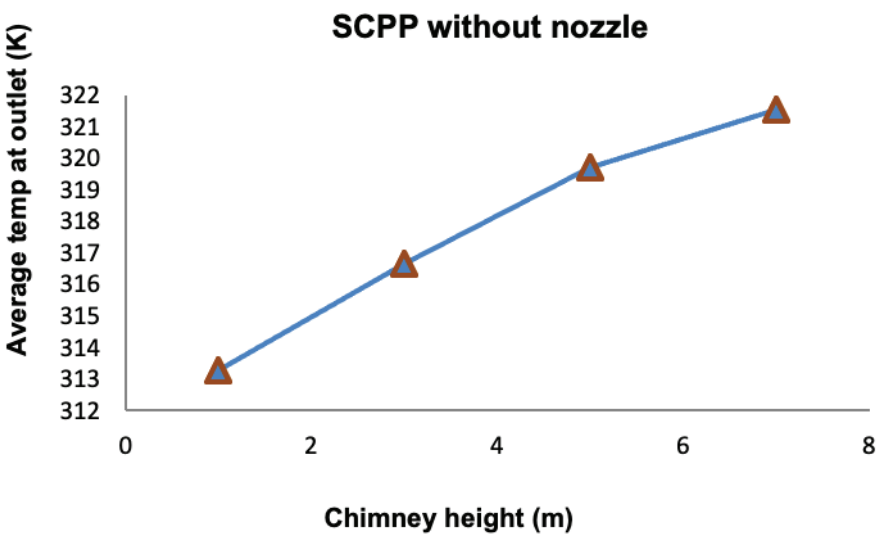


Figure 24. Comparison of Chimney height and average temperature at outlet for SCPP without nozzle (Using TM method).

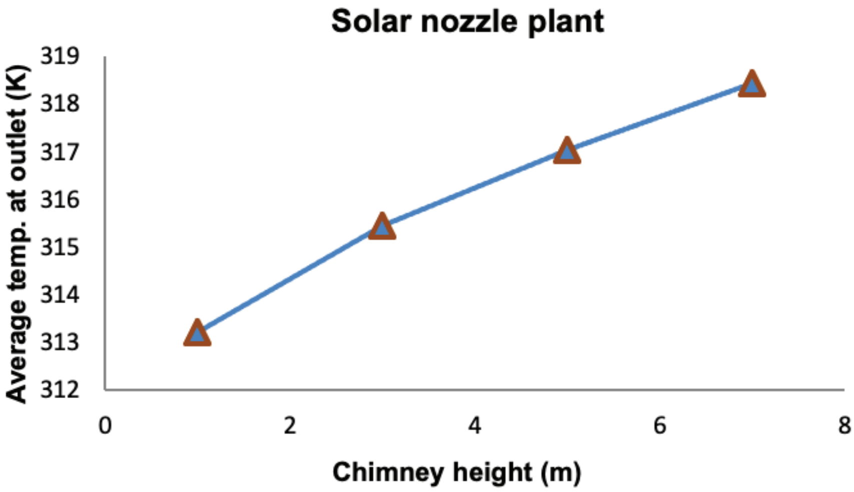


Figure 25. Comparison of Chimney height and average temperature at outlet for solar nozzle plant (Using TM method).

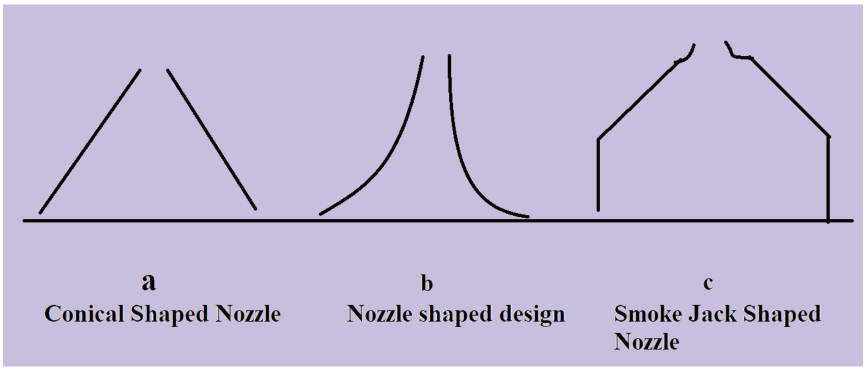


Figure 24. Different Shapes of solar nozzles [33].

CONCLUSION

Numerical analysis of all models show that as chimney height increases corresponding maximum air velocity also increases (Figures 22 and 23). Figure 23 shows that for all solar nozzle models, for both fair weather and theoretical maximum conditions the numerical results are nearer to each other. The base and inlet dimensions are kept constants for all numerical cases i.e. 3 × 3 m and inlet height = 0.1 m, respectively. Considering the 7 m height model (i.e. models 1 and 2), the solar nozzle model (model 2) shows a 16.66 % increment over SCPP model (model 1) having the same height and no nozzle. Model 4 (solar nozzle with nozzle height of 5 m) shows an increment in maximum air velocity compared to model 3 (SCPP model with chimney height of 5 m) by nearly 8.33 %. The solar nozzle model 6 with height of nozzle 3 m shows an optimum increment of nearly 29 % than the SCPP model of 3 m height and with no nozzle used. Another model i.e. solar nozzle model with a height of 1 m of nozzle shows an increment of 8.47 % than model 8.

The percentage (%) change in air release velocity for model 1 (SCPP with chimney height of 7 meters) by using the theoretical maximum solar irradiance method (TM) (Table 2) than fair weather conditions (FWC) is 18 %. Similarly, the percentage (%) change in air outlet velocities for other remaining models i.e. 2, 3, 4, 5, 6, 7, and 8 (SCPP with a chimney as well as solar nozzle designs) by using theoretical maximum solar irradiance method (TM) (Table 2) than fair weather conditions (FWC) are 13.71 %, 15.15 %, 12.58 %, 14.13 %, 12.84 %, 18.18 %, and 7.04 % respectively. The percentages of increase in air outlet temperature (K) for solar nozzle models (2, 4, and 6) compared to model 8 with nozzle height of 1 m, and using theoretical maximum solar irradiance method are: 1.07 %, 2.04 %, and 2.63 %respectively (Figure 25). Also, the percentages of rise in air outlet temperature (K) for SCPP models without nozzle (i.e. models 1, 3, and 5) compared to model 7 with chimney height of 1 m are: 0.71 %, 1.21 %, and 1.66 %respectively (Figure 24).

The main results obtained are summarized as follows:

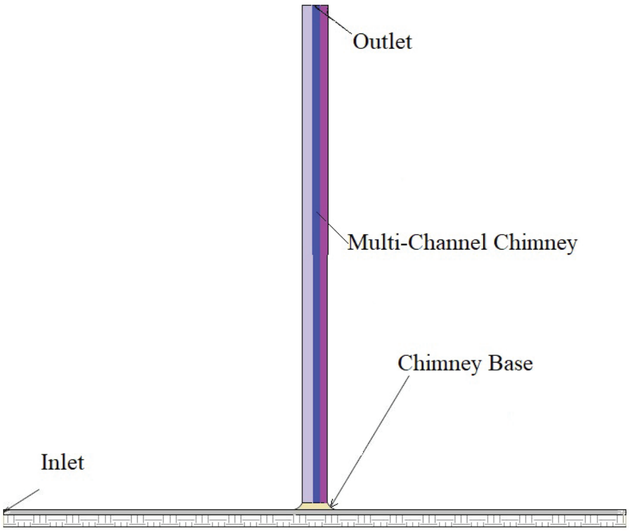


Figure 25. Multi-channel solar chimney.

1. The results demonstrate that incorporating a solar nozzle design significantly increases air release velocity compared to conventional SCPP designs, leading to a potential 16.99 (for FWC) and 12.42 (for TM conditions) % improvement in air release velocity for 7 meters overall heighted system. For 5, 3 and 1 meter heighted system design, the percentages increase in air exit velocity (comparing with and without nozzle designs for both conditions i.e. FWC and TM) changes to 8.33 (FWC), 5.92 (TM), 18.47 (FWC), 17.14 (TM), 29.09 (FWC), 16.92 (TM), respectively (Table 02).
2. This increase in air updraft velocity will have a considerable impact on the power output of the electricity generation plant when the turbine is fixed at the nozzle outlet region.
3. From Table 2, it is quite clear that, for all considered models, the maximum air release velocity is higher with the use of a solar nozzle than with no nozzle. Hence, it is found that the application of solar nozzles in SCPP design enhances air release velocity at nozzle outlet than a conventional design, thus improving power output.
4. The numerical results with theoretical maximum irradiance method show maximum air release velocity compared to fair weather conditions.

FUTURE SCOPE

Already there is an abundant amount of research work done in the field of solar updraft tower power generation plant; still there is a scope available for extending research in this field. A lot of areas like the influence of geometrical constraints on chimney performance, collector dimensions etc., overall sizing of the plant, materials selections, availability of solar radiation intensities that are based on location selections etc. are needed to evaluate further to get optimum results for the SUT. In this study, conical shaped nozzle design is used. The numerical study can further be extended to find out optimum air release velocity using smoke jack shaped and conical shaped nozzle (Figure 24). Research can be extended to evaluate the performance of using multi-channels (For example: number of multi channels = 10, 20 to 100, etc.) inside the chimney in SCPP (Figure 25) [36]. A hybrid system should be tested further to calculate the impact of various mentioned parameters on the overall performance and efficiency of SUT (For example: Integrated design of SUT using Geothermal + solar + wind energy for power generation applications).

NOMENCLATURE

H_{Nozzle}	Height of nozzle i.e. distance from solar absorber to top of the nozzle (m)
H	Height of chimney (m)
R_{Coll}	Radius of collector
R_{Chim}	Radius of chimney
$U_{tower,max}$	Maximum air velocity flowing in the tower (chimney) in m/s
P	Power output in Watts
ΔP_{tot}	Total pressure difference
P_{tot}	The total power output in watts
V_1	Inlet velocity of air flowing through nozzle (m/s)
V_2	Updarft air velocity through nozzle (m/s)
T	Ambient temperature (°C)
g	Acceleration due to gravity (9.81 m/s^2)
I	Solar insolation
ρ	Density of air
S_{etrn}	The top of the atmosphere direct normal solar irradiance
$S_{unprime}$	The correction factor used to account for reduction in solar load through the atmosphere
C	Constant
Y	The ratio of sky diffuse radiation on a vertical surface to that on a horizontal surface
E_d	The direct irradiation at the earth's surface
E_{dn}	The direct normal irradiation at the earth's surface on a clear day
ϵ	The tilt angle of the surface (in degrees) from the horizontal plane
ρ_g	The ground reflectivity
v_i	Velocity of air at chimney entrance in m/s
ΔT_i	Temperature difference at chimney entrance height
g	Acceleration due to gravity, 9.81 m/s^2
T_a	Ambient air temperature in K
h_o	Height of chimney entrance above ground in m
$n_{1,2}$	Refractive indices
$\lambda_{1,2}$	Wavelengths of solar radiations

Abbreviations

SCPP	Solar chimney power plant
FWC	Fair weather conditions

TM Theoretical maximum using solar irradiance method
PV Photovoltaic

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AUTHORSHIP CONTRIBUTIONS

All authors contributed to this work.

Anand Gondchawar: Conceptualization, Software, Validation, Writing- Original draft, review and editing. **Bhavesh Kanabar:** Funding activities, and supervision. **Ramesh Bhoraniya:** Writing- review and editing, funding activities, and supervision.

DATA AVAILABILITY

The authors confirm that the data that supports the findings of this study are available within the article. Raw data that support the findings of this study are available from the corresponding authors, upon reasonable request.

CONFLICT OF INTEREST

The authors declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

ETHICAL APPROVAL

There are no ethical issues with the publication of this research article.

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