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CFD Analysis of Solar Chimney Power Plant: Effect of Chimney Height, Shape and Collector Size

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A B S T R A C T

This paper presents computational fluid dynamics (CFD) simulation of the solar chimney power plant to analyze to analyze buoyancy-nature of heated air by har- nessing solar energy. ANSYS Fluent a finite volume code has been used for axisym- metric model of the solar chimney power plant (SCPP) prototype in Manzanares, Spain considering updraft tower. A standard k-*E* turbulence model and Boussinesq approximation for buoyancy driven flow is considered. Small pressure difference be- cause of natural draft inside the chimney during day time has been observed due to solar radiation. The numerical results obtained for average velocity and temper- ature at chimney inlet are validated with the experimental results of the prototype. It has been observed that both the velocity and temperature of air inside the SCPP increases significantly with the increment in solar radiation. Increase in the chimney height and collector radius also increases the power output of the plant. The effect of chimney convergence with different area ratio on the power output of SCCPs has been analyzed.

1. Introduction

Current power generation from the petroleum derivatives like flammable gas, oil or coal are detrimental to the earth by exposing the impediments that depend upon the sustainable power sources. Most of the developing countries cannot afford the cost of these convectional energy sources, and in the some of these areas nuclear power has been viewed as in-admissibly hazardous. Solar energy plays a great role in aspects of energy conversion diversity and resource accessibility. Non-conventional energy resources are the best options for solving problems related to CO_2 emissions enhancing environmental pollution. However, the modern scientists are looking for controlled use of fossil fuels to counteract the inevitable shortage of energy sources. SCPP is one of the non-conventional energy systems and the best alternative toanalyze the characteristics of the solar chimney power plant with different geometrical and operational parameters. In the mid 1900s, Spanish Colonel Cabanyes proposed that the energy from the air could be utilized to generate power. Researcher tried Cabanyes hypothesis in the 1980s, by building a solar chimney power plant prototype. A prototype was built in Manzanares, Spain as shown in Fig.1 which was operational for most of the 1980s. The solar air collector in form of a circular glass transparent open roof has been used to heat the air in the space between ground and solar collector by using solar radiation. A vertical chimney is placed at the collector center having air inlet opening at the most lower section or collector outlet (or, chimney inlet) throughout the chimney length up to the exit section. As the air is heated underneath of the collector, the density of the air decreases so that the air inside thesolar chimney power plant is lighter than the ambient air that causes air to start rising up to the exit of the tower. As more hot air from the collector is drawn up tothe suction of the chimney, cooler air comes in from outer periphery of the collector due to buoyancy effect. In the process, fluid kinetic energy converted into mechanical energy by spinning the pressure-stage turbine installed at chimney inlet and finallyto electric power by conventional generator.

Dai et al. [1] designed SCPP expecting to provide electric power for the remote area of north west china. They considered Yinchuan, Pingluo, and Helan regions of chine where better solar radiation intensity is available. A SCPP having 200m height and 10m diameter chimney and 500m diameter of the collector was capable of pro- ducing electric power of 110-190 kW on a month average all the year. They analyzed parameters affecting the performance of SCPP such as ambient temperature, solar irradiation, height of the chimney, diameter of the collector and turbine efficiency.

Pastohr et al. [2] used CFD model with ANSYS Fluent software to analyze SCPP by generating axisymmetric model of solar chimney based on Spanish proto- type including 2m ground surface as a thermal storage for the power plant and results show that higher fluid velocity and temperature throughout the tower are attained for higher energy in the system. Radiation model was not included in this simulation, instead the authors modeled the solar radiation as a heat source in a thin layer on underneath of solar collector. It was concluded from the simulation that the more energy in the system, the higher fluid velocity and temperature throughout the tower. Authors concluded that the time dependent simulation needed to appropriately calcu- late heat transfer between the air and the ground. Pretorius et al. [3] Studied the effects of nearly developed convective mode of heat transfer equation. Results show that this nearly developed equation considerably reduces the effects of the coefficient of the turbine and power outputs of the plant. Ming et al. [4] performed nu- merical simulation to analyze heat transfer and air flow characteristics in the SCPP with the energy storage layer. They found that for solar radiation from 200 W/m^2 to 800 W/m^2 heat storage ratio decreases and then increases, relative static pressure reduces while velocity increases significantly, and average temperature of the chimney outlet and energy storage layer increases. The temperature gradient of the storage layer increases which increases energy loss. Ming et al [5] studied performance of the Manzanares prototype SCPP with the turbine using numerically simulation. The result indicates that the Manzanares prototype can generate power up to 50KW. Additionally, they analyzed the effects of the turbine rotating speed on the outlet pa- rameter of the chimney and used as the validation of the numerical model. Xinping et al [6] have studied the maximum and optimum height of the chimney for maximum power output neglecting the negative effects of the buoyancy force at chimney inlet. The theoretical analysis on SCPP has been validated with experimental values of prototype Manzanares. They taken dimensions of the prototype as a reference and based on that taking standard rate of atmospheric temperatures for optimal chimney height with 615m the optimum and maximum power output was 102.2kW and 92.3kW respectively for the maximum height. Authors concluded that to get maximum power conversion efficiency the plant needs to have chimney height equal to the optimum chimney height. Lorente et al. [7] have shown how to use constructal design to distribute solar chimney power production on available land efficiently. They found that the power generated per unit land area is proportional to the length scale of the power plant, chimney height, roof radius, and chimney radius. Xu et al. [8] have performed numerical simulations for air flow, heat transfer and power output of a solar chimney power plant with thermal storage and turbine on similar to Spanish prototype. The effect of solar radiation and pressure drop in the turbine on the flow and heat transfer, output power and energy loss were analyzed. They found that for solar radiation of 600 W/m^2 and turbine efficiency 80 %, the output power of the plant can be 120 kW. Mass of air leaving the chimney and collector canopy results in large energy loss. Ming et al. [9] have studied the effects of crosswind of ambient on the power output of the SCPP in both air inlet and outlet. Authors dealt with the negative impacts of the ambient crosswind on the performance of SCPP. Additionally authors intended to overcome the negative impacts of ambient crosswind in both inlet and exit of the SCPP by taking the Manzanares prototype with the same dimension and 2m high blockage was built circularly a few distances away from collector inlet. A mathematical model with geometric model of SCPP including outside ambient was built. The mathematical model for describing the transfer of heat, flow of the fluid and the power outputs of the solar chimney power plant was developed. Velocity, pressure and temperature of air both outside and inside of the solar chimney power plant with the power output from the plant has been analyzed. According to numerical simulation of this paper the negative impacts of ambient crosswind has been overcome using blockage around the inlet of the collector to a great extent.

Li et al. [10] developed theoretical model considering equation of thermal equi- librium inside the collector, system pressure difference, and flow loss using existing measured data. The model has been validated using Spanish prototype, Manzanares. They concluded that comparing to unloaded conditions, installation of the turbine will decrease the power output of SCPP system. At certain solar radiation intensity, thereis a maximum power output of SCPP. There is a limitation on the maximum collector diameter after which the output power reduces and eventually gets constant. Choi etal. [11] developed analytical method to study the power output of the plant and temperature configuration of the collector. They used experimental measurement ofthe Spanish prototype for validation purpose. Additionally water was used as energy storage medium to heat cold air during the night time. Fasel et al. [12] used CFD analysis sung ANSYS Fluent software to investigate the performance of SCPP. Some analytic verification of scaling laws by considering a chimney height between 1m (labo- ratory model) to 1000 m (the envisioned large power plant) have been analyzed. At the University of Arizona a 6m model chimney height was under construction. They found that the simulation of high resolution time dependent of flow through collector to the chimney of the model help insight detail into the mechanism of fluid dynamics and transfer of heat. Convection rolls both longitudinal and transverse are identified indi- cating the presence of Rayleigh-Benard-Poiseuille instability inside the collector. They found that near the chimney inflow and inside the chimney there is local separation and fully turbulent flow respectively. Cao et al. [13] built a TRNSYS (Transient System Simulation) program to simulate the performance of the SCPP due to difference of weather conditions from place to place. It is found that the SCPP power generation is more relevant to the local solar irradiation than to the ambient temperature. TheSCPP with higher generation capacity are more cost-economic. Ming et al. [14] nu- merically computed the performance of the solar updraft power plant system (SUPPS) of 50KW model with same dimensions as the Manzanares, Spain through the collector inlet a 2m high blockage few meters away from the collector inlet to overcome the cross wind effect. It was found that the negative effect of the ambient crosswind have been overcome to a large extent. Koonsrisuk et al. [15] presented performance of SCPP using second law efficiency with the different configurations of the power plant. Some comparison has been made between conventional and sloped type of SCPP. The results indicate that there is an optimum size of the collector that gives maximumand minimum second law efficiency and entropy generation respectively. Based on the result, the second laws of efficiency increases for both conventional SCPP and sloped SCPP, when the chimney height increases. Authors also found that Sloped SCPPs are thermodynamically better than conventional SCPPs for some configurations. A. Koon- srisuk and T. Chitsomboon A. Koonsrisuk et al. [16] studied changes in the flow properties caused due to variation of flow area. They found that sloping of collector roof affects the performance of SCPPs and divergent top chimney leads to significant increase in air velocity at chimney base. The proper combination of sloping collector and chimney divergent can produce power as much hundred times that of conventional SCPP. Sandeep et al. [17] used CFD to optimize and improve SCCP geometry such as chimney top angle and collector inlet diameter along with air flow characteristics inside the SCPP. The air inlet opening was varied from 0.05m to 0.2m height from the ground and radius of collector at outlet from 0.3m to 0.5m for the collector diameter and chimney height 20m and 4m respectively. They also tested the chimney angle of divergence (0^o - 3^o) and chimney inlet opening (0.25m - 0.3m) for the modified SCPP. Based on their computation, results show that 2^o, 0.125m , 0.05m and 0.5m chimney top divergent angle, radius, and collector inlet and outlet respectively. Okada et al. [18] applied a diffuser tower instead of a cylindrical shape in a laboratory size CFD model and they found that static pressure recovery effect makes low static pressure region at the bottom of the tower. This effect increased flow rate of air within the tower and found that proposed diffuser shape tower induced velocity 1.38-1.44 and power 2.6-3.0 times greater then that of cylindrical shape tower. Gholamalizadeh et al. [19] simulated three dimensional SCPP to analyze the greenhouse effects of the plant using ANSYS Fluent software with discrete radiation model. They studied the effect of solar irradiation focused on the collector and the temperature and velocity of the chimney system. They concluded that incorporating the greenhouse method plays a great role to the model of SCPP to accurately model the heat transfer in the system.Cottam et al. [20] analyzed thermodynamics of the SCPP collector under steady state analytic and assessed the effects of different shape of the collector roof design in the power output of the SCPP. They showed that the collector height from the ground should be sufficient high at chimney inlet to get maximum kinetic energy at chimney inlet where the turbine is mounted. The authors proposed a partial canopyprofile and they found it to the best performing existing design of collector for SCPP and robust under different environmental condition. Huang et al. [21] conducted numerical simulation for the Manzanares plant using two parallel plate model consid- ering radiation within the collector. Their simulation results are consistent with the three-dimensional methods of open literature and experiments.

Semai et al. [22] analyzed the collector cover slope effect on the performance of the SCPP. The ground and water was used as a thermal storage material. The minimiz- ing entropy production, geometric configuration and collector cover shape have been considered on the efficiency of the SCPP. The thermal storage media and geometric configuration improve the velocity at the chimney entrance. Rabehi et al. [23] considered four locations in the Algeria and performed numerical simulation of SCPP using ANSYS Fluent software. Thy found that highest power pro- duced monthly average was 68-73 KW over a year and highest hourly power produced in the month of June was around 109-113 KW. X. Zhou et al. [24] examined the effect of flow area parameters on the fluid power and turbine pressure drop factor of solar chimney power plants. They recommended divergent top solar chimney for better performance of the power plant. Shiyang et al. [25] studied the effect of area ratio of chimney exit to entrance, divergent angle of wall and size of the system. The results indicated a significant enhancement in the over all performance of the divergent SCPPs over the cylindrical - chimney systems. Yangyan Xu et al. [26] conducted simulation of diverging chimney solar power plant and found that with chimney outlet to inlet ratio increasing, the total pressure potential, mass flow rate and power output initially increases and reaches to maximum for area ratio 8.7 and then decreases. A maximum power of 231.7kw was attained at area ratio of 8.7, which is 11.9 times high as that for area ratio of 1.

A little efforts have been carried out toward the study of the effects of the geometry and solar radiation on the power output of SCPP. The main objectives of the present work is to study the effect of solar radiation, chimney height, collector diameter and chimney shape (top convergence) on the power output of SCPP using ANSYS Fluent software.

2. Materials and Methods

2.1. Problem formulation

The experimental data from the Manzanares prototype shows the power output (P_t) of the plant can be predicted based on the thermodynamic analysis of solar chimney (Fasel et al. (2013)).

$$P_t = \eta_{ch}\eta_c \frac{2}{3} g \frac{H_{ch}\pi R^2 I}{C_p T_a} \qquad (1)$$

where η_{ch}, η_c, g, H_{ch}, R, I, Ta are efficiency of chimney and collector, gravitational potential, chimney height, radius of the collector, solar irradiance, and ambient tem-perature respectively. The solar solar radiation that heats the collector is responsible for natural convection induced inside the SCPP. Rayleigh number (R_a) has been used to measure the induced buoyancy intensity of the flowing fluid inside the solar chim- ney[8].

$$R_a = \frac{g\beta\Delta T L^3}{\alpha\nu} \qquad (2)$$

where ΔT is the maximum change in temperature inside the SCPP, L is the height ofthe collector inlet, β is thermal diffusivity, α is coefficient of thermal expansion, and g is gravitational potential. In the present investigation, Rayleigh number has been found to be greater than 1010, which is a criterion for transition from laminar to turbulent flow for convection. Therefore, authors have included turbulence modeling in the present study to describe the fluid inside the SCPP. Fig.1 shows the schematic dia-gram of SCPP. The governing equations, continuity, momentum, energy and standard k-*E* equations are solved numerically.

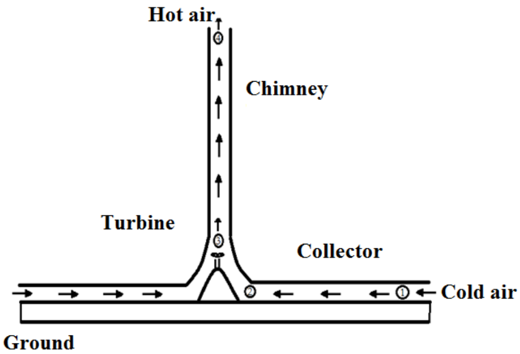

Figure 1. Schematic diagram of updraft solar chimney power plant

2.2. Boundary conditions

The boundary conditions considered in the present simulation of the SCPP are listed in the Table 1. The wall of the chimney is considered as adiabatic wall. Furthermore, constant temperature conditions is applied to ground. 5m radius of soil with 5m depth is included in the simulation of the model. All the side faces of energy storage layers are considered to be adiabatic.

1.3. Numerical considerations

Axisymmetric model of SCPP with steady numerical computation consideration of turbine into the system has been studied. Because 2D turbine describes only flow characteristics of the plant considering ideal pressure drop. To estimate the power output of the SCPP in the CFD simulation velocity distribution and average velocity of the air has been computed.

2.4. System description

In the present simulation, a physical model of the Spanish prototype, Manzanares is taken as shown in Fig.1. The prototype has 195m height and 5m radius of the chimney and collector with 120m radius and 1.7m height from the ground. The Boussinesque approximation is valid for the present simulation case.

2.5. Computational simulation

The governing equations, continuity, NavierStokes, and energy equation were solved using the SIMPLE algorithms and the calculations were carried out using ANSYS Fluent. The dimensions are taken from the available Spanish prototype of SCPP for the computations. To show the flow and heat transfer characteristics of air inside power plant, the two-equation turbulence model of a Standard k-E model and for near wall treatment, standard wall function is used. For radiation model, the one presenting better radiation energy transfer phenomena than the other commonly used comparatively and capability of applying direct solar load which is discrete ordinates (DO) model is selected. The convective and diffusive terms were discretized with a second order accurate upwind scheme. Chimney, soil and collector were discretized using the Quad meshing scheme. The pressure and velocity equations are coupled using SIMPLE algorithm. Turbulence, momentum, energy and radiation equations are solved using second order upwind scheme. The Least Squares Cell-Based evaluation is used for the spatial discretization of the gradient.'

2.6. Grid conversion test

The bend was meshed using the Quad/Tri meshing scheme since it has irregular ge- ometry. The number of cells inside the collector and chimney tower were 34 × 380 and 34 × 460, respectively. The total number of cells including the ground were around 190,960. Based on the grid independence study, authors choose to use the grid #3 in all simulations in the present study.

Table 1. List of boundary conditions for solar chimney power plant simulations

Boundary	Type	Conditions
Chimney wall	Wall	$q_{ch} = 0$ W/m^2
Collector	Wall	h = 8 W/m^2; $T\infty = T_{amb}$
Ground	Wall	T = 302 K
Deflector	Wall	$q_{ch} = 0$ W/m^2
Collector inlet	pressure inlet	$\Delta P_{in} = 0$; $T_{in} = T_{amb}$

Chimney Outlet	pressure outlet	$\Delta Pout = 0$; $Tout = Tamb - 0.065 \times H_{ch}$

Table 2. The grid convergence study for the velocity profile of chimney is obtained. The successive grid refinement ratio in both the direction is 1.4142. The relative error was computed using two consecutive grid size

Mesh	Grid size	average velocity	% error E
#1	230 × 17	$6.05e^{-7}$	-
#2	326 × 24	$6.79e^{-8}$	0.8
#3	460 × 34	$2.32e^{-8}$	0.65
#4	648 × 48	$2.23e^{-8}$	0.04
#5	912 × 68	$2.18e^{-8}$	0.022

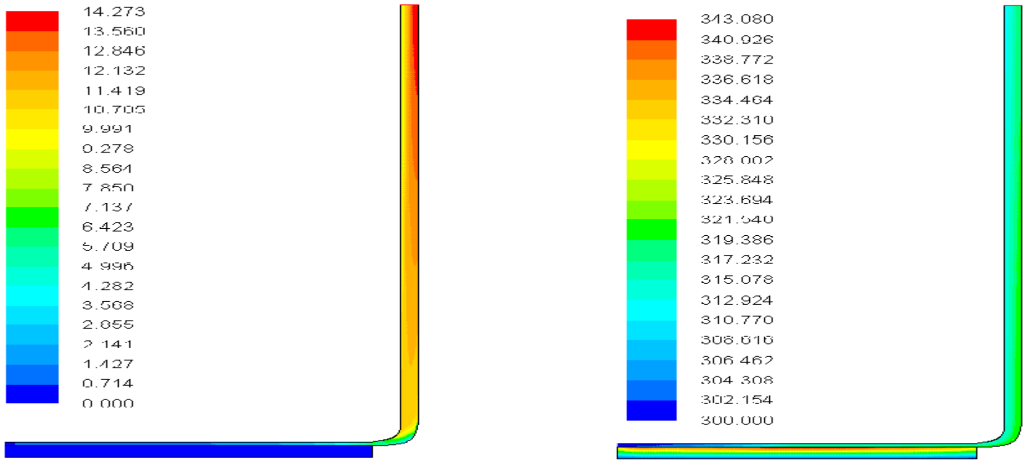

Figure 2. Contour plot of (a) velocity (b) temperature of SCPP with soil as thermal storage

3. Results & Discussion

The velocity starts to increase sharply at chimney inlet. Experimental results for Manzanares prototype (with load) showed average chimney inlet velocities between 7-9 m/s where as 15-20 K of maximum air temperature rise [12]. The temperature rise in the collector determines the efficiency of the collector. Figure 4(a) and (b) shows the contour plot of velocity and temperature respectively. The computed average velocity and air temperature rise are 10.7 m/s and 22k respectively. The average velocity and temperature are computed taking integral average of this contour plot. It is found that air velocity increases at the chimney inlet when moving from the collector. The maximum temperature is found under the collector. The numerical simulation results are in good agreement with the Manzanares experimental results which shows that the numerical simulations considered are quit reliable. The small difference in the velocity and temperature results are due to the presence of turbineat the inlet of the chimney which leads to velocity reduction. In the present work, the analysis of the SCPP is performed without considering the turbine at the inlet of chimney. We considered axisymmetric geometry of the solar chimney and uncertainty of some parameters, like the density and humidity of the air.

3.1. Effect of radiation intensity

Figure 3(a) and (b) shows the velocity distributions in the SCPP with soil as thermal storage material for radiation intensity of 400 and 1000 W/m^2 respectively. From the Fig.3 it is found that air velocity increases as solar radiation intensity increases fro 400 to 1000 W/m^2. The maximum velocity is found at chimney inlet. The maximum attained velocity in the chimney are 11.8, 14.1 and 15.7 m/s for radiation intensity of 400, 600 and 800 W/m^2 respectively. The maximum chimney inlet velocity without turbine is around 22.5 m/s for solar radiation intensity of 1000W/m^2. So it is evident that solar radiation plays a great role in the velocity of the flowing air by increasing the temperature under the collector which in turn increases the density difference by creating buoyancy force and thus pressure difference is generated. Figure 4 presents variation of velocity inside the collector for different radiation intensity. The velocity (Maximum OR average) increases towards the chimney and with the increase in radiation intensity. Similarly Figure 5 and 6 shows the distribution and variation of air temperature inside the collector for different radiation intensity. The temperature of air also increases towards the chimney with the increase in radiation intensity.

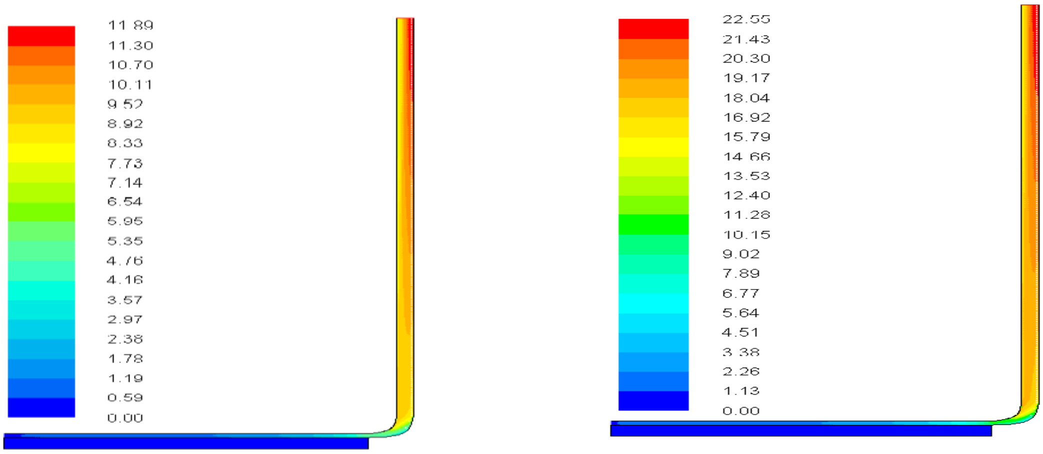

Figure 3. Velocity contours of SCPP for different radiation intensity (a) 400 W/m^2 (b) 1000 W/m^2

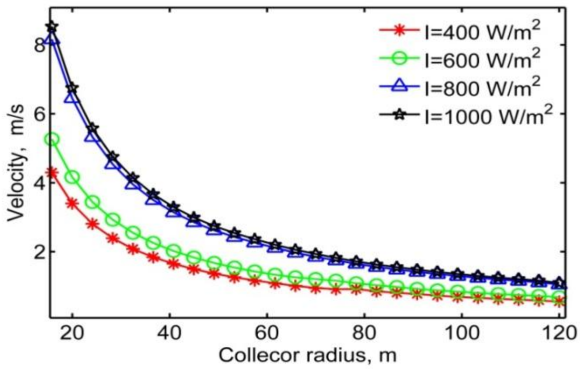

Figure 4. Velocity distribution in the SCPP with various solar radiation intensity

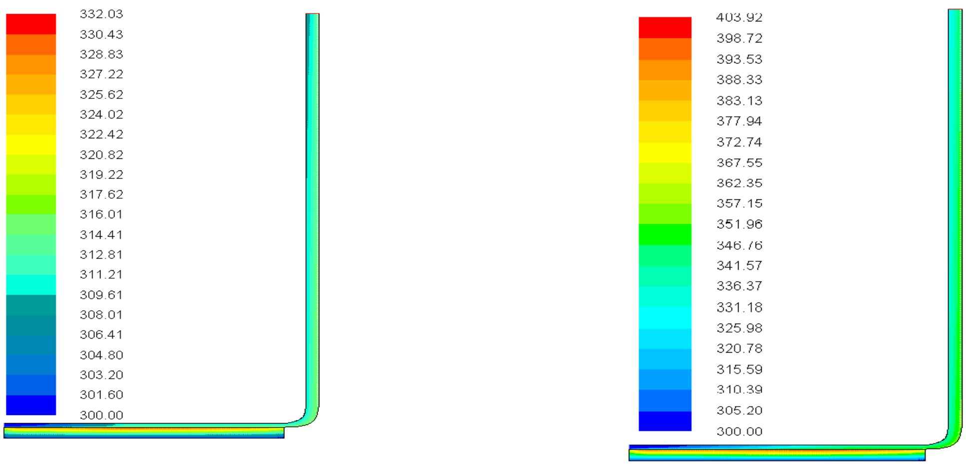

Figure 5. Temperature contours of SCPP for different radiation intensity (a) 400 W/m^2 (b) 1000 W/m^2

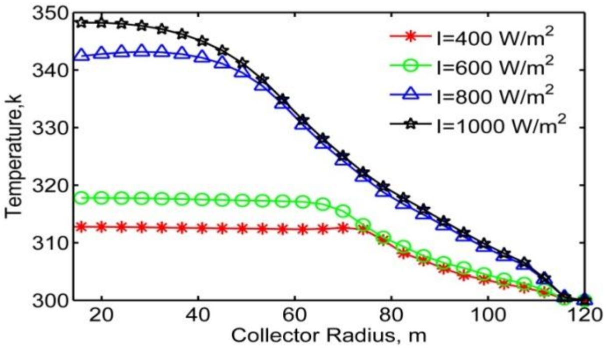

Figure 6. Temperature distribution in SCPP with various solar radiation intensity.

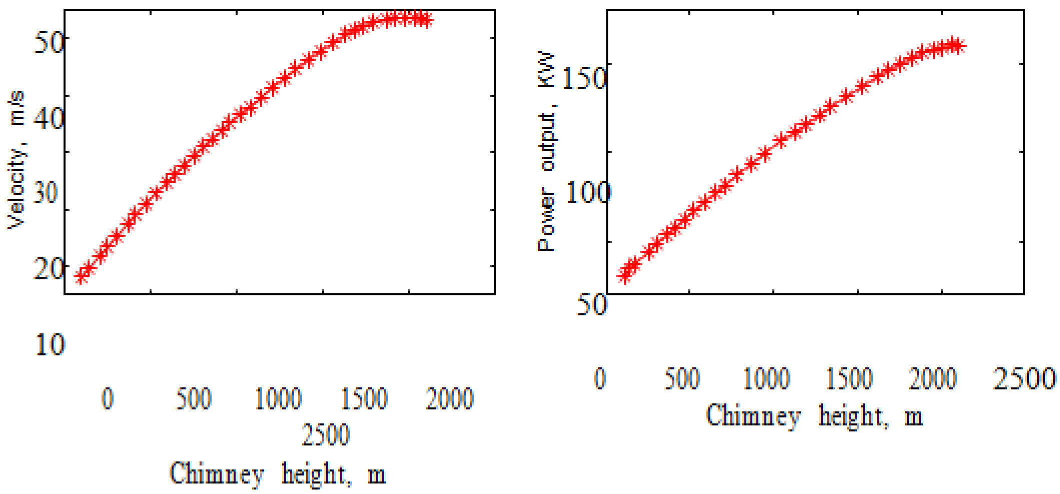

Figure 7. Effect of chimney height on (a) velocity (b) power output of SCPP.

3.2. Effect of chimney height

The low density air provoked by the rise of temperature under the roof is converted to kinetic energy inside the chimney of SCPP. It has been reported that power output of SCPP is directly proportional to the height of the chimney under unloaded condition (Reference). The air temperature in side the chimney either decreases or remains almost constant due to gravitational potential energy. Thus, the buoyancy effect of air inside the chimney reduces with the increased chimney height. In the present study, Manzanares prototype with the same dimensions excepting the chimney height with irradiance of 1000 W/m^2 is considered to investigate the effect of chimney height on the performance of SCPP.

The maximum velocity and power output have been chosen the indicator of the powerharnessed by the SCPP. Figure 7 (a) and (b) show the effect of chimney on the velocityand power output respectively. Since the power output is directly proportional to theheight of the chimney, it is obvious that the power output increases as chimney height increases. However the rate of increase has been reduced continuously. The reason of this decrements is due to weakening of buoyancy and flow loss. Figure 7 (b) shows that based on the dimension of Manzanares prototype, result shows that chimney heightof 1900 m is the maximum height of the chimney to generate maximum power, above which the power will no longer increases.

3.3. Effect of collector diameter

Power output of the SCPP is directly proportional to the square of collector radius according to theoretical performance of SCPP with unloaded condition for a given chimney height.

Therefore, in the present study the maximum collector radius of Manzanares proto- type is taken as example as proposed in theoretical model with solar radiation of 1000 W/m^2 and main dimensions of the prototype are kept constant apart from the radius of the collector. The maximum velocity point is selected for every collector radius as performance of SCPP.

The velocity of air inside SCPP increases apparently as the collector radius increases up to 320m as shown in Fig.8. However, the increment of the velocity and power out- put reduced slowly up to 395m and eventually almost remain constant when radius exceeds 395m. Therefore we can say that the maximum radius of the collector for Manzanares prototype is 395m beyond which power output remains almost constant. An excessive heat loss is the main reason of this limitation. The heat loss is from roof to sky, atmospheric air and from the ground to deep soil by radiation, convection and conduction respectively. Thus, 395m radius is the maximum radius of the collector above which no power output will not change irrespective of the collector cost.

3.4. Effect of Chimney shape

In this section the effect or influence of the chimney cross-section on the performance of SCPP has been discussed. To study the effect of the convergent shape of the solar chimney, it is modeled with different outlet to inlet area ratio of the chimney and numerically solved using ANSYS Fluent. Figure 9 shows that the velocity variation w. r. t. height of the chimney for different outlet to inlet area ratio of the chimney.It has been observed that for any area ratio (AR), the velocity inside the collector always increases as it approach chimney inlet. However, inside the chimney velocity depends on an outlet to inlet area ratio of the chimney. Different four area ratio for the convergent shape of the chimney have been considered are AR = 0.25, 0.5, 0.75, and 1. The Manzanares prototype is having uniform diameter of the chimney i.e AR = 1.0The velocity of the air inside the chimney keeps increasing and attains maximum valueat the chimney exit for all convergent shape of chimney with AR smaller then one. Figure 9 shows that as AR decreases, the velocity of air at chimney inlet increases as compared to that of chimney with uniform diameter.

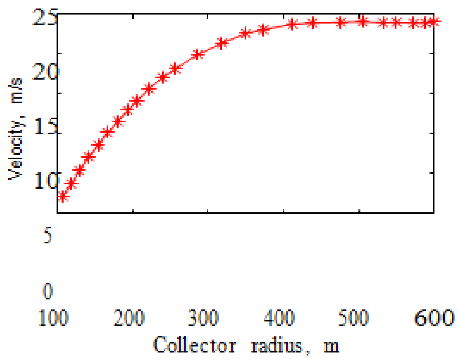

Figure 8. Effect of collector radius on the air velocity. The chimney height is taken 120m.

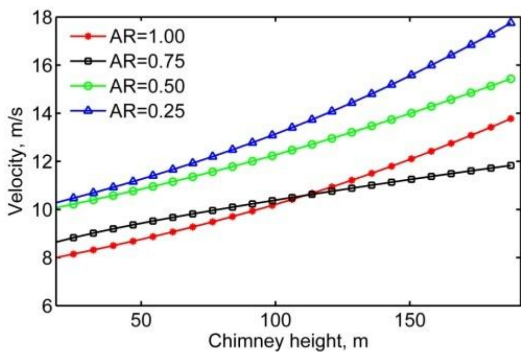

Figure 9. Effect of chimney top convergence on average velocity.

4. Conclusions

A Numerical computations have been performed on the commercially available finite volume code, ANSYS Fluent. The effect of radiation intensity and plant geometry have been incorporated in the model based on the Manzanares prototype. The velocity of the air increases, as solar radiation increases inside the SCPP. Additionally as chimney height and collector diameter increases, the power output of the SCPP increases. How- ever, there is a limitation for both maximum chimney height and collector diameter above which the attainable power output increases with decreasing rate and finally get to constant. A chimney with convergent shape with different area ratio, it is found that velocity at the chimney outlet increases with increased area ratio. Additionally it improves the chimney inlet velocity where turbine is to be installed compared to the uniform cross sectional area chimney. However, it may not be a viable design since the velocity at chimney exit is very high compared to that of chimney inlet, it needs installation of the turbine at the top of the chimney, which increases the cost of tur- bine installation and difficult for maintenance and accessibility of the turbine on the convergent section, despite it increases power output of the power plant.

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