Numerical Study of the Influence of Geometric Variation of the Tower on the Inflow Air Velocity of one Solar Chimney Power Plant

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energy from solar radiations to mechanical powers. In this study, the influence of geometric variation of the tower on the Air Velocity of one SCPP is numerically investigated. Regarding the importance of the kinetic power of the hot air on power generation of SCPP, This article aims to propose an approach to increase the air velocity by considering the various forms of the chimney without changing the main dimensions of SCPP. This approach increases the efficiency of the power plant. For the numerical simulations, a commercial CFD code solves the governing equations using the finite volume method. To simulate the problem in the 3-dimensional setting, by cutting a 15 degrees wedge out of the whole power plant geometry, a pi-shape domain is created. In order to validate the obtained results, the Manzanares Power Plant experimental data are utilized. In this study, ten forms of chimney wall based on a logical procedure (from a cylindrical form to a convergence/divergence form) are examined. By considering this procedure, an appropriate divergence form for the chimney wall is obtained. These results indicate that the final form (i.e. the divergence form of the chimney wall) has the highest updraft air velocity which is an important factor on wind turbine power generation. In addition, the average updraft air velocity increases from 15.66 m/s for the basic form to the value of 22.52 m/s for the best form (form 7), (i.e. the increment of around 43.81%).

keywords: *Solar Chimney Power Plant, Numerical Study, Solar Chimney, Form of Chimney, airflow Velocity.*

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NOMENCLATURE

D_S Soil depth [m]

D_{Tu} Turbine diameter [m]

f Exploitation factor, dimensionless

H Height [m]

p pressure [Pa]

R radius [m]

S_E source term in the energy equation [W/m^3]

S_M source term in the momentum equations [N/m^3]

T temperature [C]

U Air velocity [m/s]

Greek symbols

ΔP pressure drop [N/m2]

ρ density [kg /m3]

Subscripts

B Base of chimney

BJ Bend junction

C Collector

CI Collector inlet

CO Collector outlet

S Soil

SC Solar chimney

T Tower

TI Tower inlet (Chimney inlet)

To Tower outlet (Chimney outlet)

1. INTRODUCTION

A solar chimney power plant (SCPP) is a renewable power technology which is able to convert heat energy of solar radiations to mechanical powers. This kind of solar power plants consists of three main parts including a collector, the turbo-generator(s) as a power conversion unit, and the solar tower [1]. The hot airflow is allowed to pass through the tall chimney and it is then applied to drive the turbo-generator(s) which will generate the electrical power. Actually, the tower is the thermal driving engine of these power plants which works based on natural convection and air density difference between the base and top of the tower. Since SCPPs are using solar radiation as fuel, they are entirely free of carbon emissions, when they are operating. As a result, SCPP is the most sustainable power plants that generate power by using natural resources [1].

Research efforts on SCPP are categorized by a number of numerical and theoretical studies, but with inadequate experimental work. The idea of using a solar chimney to produce electricity was first proposed in 1903 by the Spanish engineer Isodoro Cabanyes [2, 3] and until the late twentieth century, some researchers had studied on SCPP and proposed some ideas for executing such power-plants. Finally, the experiments accomplished on the first prototype in Manzanares of Spain, by Schlaich (1982), (a chimney diameter 10 m, a height 195 m and a collector diameter of 240 m), for a 50 kW wind turbine, have shown that the concept of SCPP is technically feasible [4, 5].

After designing and construction of the Manzanares power plant, studies and researches about SCPP are developed on many elds. Several thermodynamic and numerical studies analyzed the design parameters of SCPP and obtained mathematical models to establish performance, efficiency, and economy of the plant. For example, in 2003, Bernardes et al. [6] developed a comprehensive analytical and numerical model for simulating the performance of the SCPP. In 2003, Dai et al. [7] analyzed a solar chimney power plant for remote villages in northwestern China. In 2004, Pastohr et al. [8] carried out a numerical analysis to improve the description of the operation mode and efficiency of the upwind power plant by FLUENT. In 2005, Bilgen and Rheault [9] investigated a novel solar chimney system (the sloped collector eld, which also acts as a chimney with a short vertical chimney to install the vertical axis air turbine) for power production at high latitudes. In 2006, Ninic [10] analyzed the available work potential of the atmospheric air that acquires while passing through the collector of a SCPP. In 2007, Burek and Habeb [11] did an experimental investigation into heat transfer and mass ow in thermos-syphoning air heaters, such as solar chimneys and the Trombe Walls. In 2008, Fluri and Backström [12] compared three congurations to the performance of the power conversion unit (PCU) of a large SCPP and its interaction with the plant from an efficiency and energy yield point of view. In 2010, Zhou et al. [13] investigated an alternative method of heat and moisture extraction from seawater under the collector of a solar chimney system for power generation and seawater desalination. In 2012, Hurtado et al. [14] analyzed the thermodynamic behavior and the power output of a SCPP over a daily operation cycle, through a numerical modeling under non-steady conditions. In 2012, Hamdan [15] developed a mathematical thermal model for steady state airow inside a SCPP which using modied Bernoulli equation with buoyancy effect and the ideal gas equation. In 2013, Koonsrisuk and Chitsomboon [16] developed a theoretical model of a solar collector, chimney, and turbine of one SCPP. In 2014, Guo et al. [17] developed a comprehensive theoretical model by taking into account the hourly variation of solar radiation to obtain a more accurate prediction of the annual performance of SCPPs. Furthermore, the optimization of the components of the system was studied and analyzed in several kinds of research. For example, in 2009, Zhou et al. [18] analyzed the maximum chimney height for convection avoiding negative buoyancy at the latter chimney and the optimal chimney height for maximum power output. In 2009, Koonsrisuk and Chitsomboon [19] developed ve simple theoretical models to compare the predictions of performances of SCPPs. In 2010, Larbi et al. [20] studied the performance analysis of a SCPP expected to provide the remote villages located in the Algerian southwestern region with electrical power. In 2013, Ghalamchi et al. [21], investigated the performance evaluation of SCPP by FLUENT software by changing three parameters including collector slope, chimney diameter and entrance gap of a collector. In 2013, Filkoski et al. [22] analyzed the technical features of SCPP by using of CFD approach, as a way for effective optimization of the object's geometry and thermo-fluid aspects. In 2014, Patel et al. [23], optimized the geometry of the major components of the SCPP by using ANSYS-CFX software to study and improve the ow characteristics inside the SCPP. In 2015, Vieira et al. [24] analyzed the influence of some geometric parameters on the available power in the SCPP and its physical principle by a numerical study.

The current study investigates numerically the effect of chimney geometry variation on the performance of a 1.0 MW SCPP with predetermined tower height, collector diameter, collector inlet opening, collector outlet height and chimney (tower) inlet opening. Regarding the importance of the kinetic power of the hot air (inside the chimney) on power generation of SCPP, This article aims to propose an approach to increase the air velocity by considering the various forms of the chimney without changing the main dimensions of SCPP such as tower height and collector geometries. The desired geometrical parameters are vertical section convergence and divergence of the tower (tower convergence and divergence angles). The variation of these parameters on improving the airow velocity inside the SCPP chimney are investigated. For the numerical simulations, a commercial CFD code solver of the finite volume method is implemented. To simulate the problem in the 3-dimensional setting, a pi-shape domain is created by cutting a 15 degrees wedge out of the whole power plant geometry. In order to validate the obtained results, the Manzanares Power Plant experimental data are utilized. This study ten forms of chimney wall based on a logical procedure are investigated. These forms are based on cylindrical and convergent/divergent geometry of the chimney wall. The obtained results included the maximum and average updraft air velocities inside the tower. After performing this procedure, an appropriate divergent form for the chimney wall is considered. The results demonstrate that the final form (i.e. form 7 with the divergent geometry of the chimney wall) has the highest updraft air velocity, which is an important factor on wind turbine power generation. It is worthwhile to mention that, the average updraft air velocity increases from 15.66 m/s for the basic form to the value of 22.52 m/s for the final form 14 (i.e. around 43.81% increment). It should be noted that the main novelty of this study is to propose an approach to increase the performance of the SCPP (i.e. increase the updraft air velocity)

Table 1. Main dimensions of the basic form of a 1.0 MW SCPP, proposed for improving its performance

Geometric parameters	Values
Height of the tower (chimney) (H_T)	280 m
Radius of the tower inlet (R_{TI})	20 m
Height of the collector inlet (H_{CI})	2.0 m
Height of the collector outlet (H_{CO})	6.0 m
Radius of the collector (R_C)	500 m
Turbine diameter (D_{Tu})	40 m
bend junction radius (R_{BJ})	5.0 m
the soil depth (thermal storage) (D_S)	1.0 m

Table 2. Different congurations of the Tower (Chimney) forms analyzed in the present work.

Samples	Convergence or divergence angle (degree)	Chimney outlet diameter $2R_{To}$ (m)	Geometry of tower wall
Form 1	-0.50°	36.00	Convergence straight line
Basic form	0.0°	40.00	Cylindrical form
Form 2	1.00°	49.39	Divergence straight line
Form 3	1.50°	54.09	Divergence straight line
Form 4	2.00°	58.79	Divergence straight line
Form 5	2.50°	63.49	Divergence straight line
Form 6	3.00°	68.19	Divergence straight line
Form 7	3.01°	68.30	Divergence straight line
Form 8	3.02°	68.40	Divergence straight line
Form 9	3.50°	73.16	Divergence straight line

by finding a suitable form of the chimney (i.e. divergence angle of tower wall) without changing the main dimensions of the SCPP (i.e. tower height, collector diameter, collector height, and etc.).

2. PHYSICAL MODEL

In this study, a 1.0 MW SCPP with the main geometry is selected (see Table 1). Regarding the importance of the kinetic power of the hot air flowing inside the chimney on power generation of SCPP, The authors aimed to propose an approach to increase the air velocity by considering the various forms of the chimney without changing the main dimensions of SCPP. In order to obtain a suitable form for the chimney, logical steps of the simulation are taken. The detail of these steps and their properties are given in Table 2 and Fig. 1.

In this study, a straight chimney wall with the convergence angle of -0.5° through divergence angles of 3.5° is set to change the geometry of the chimney. During the simulation of these forms, the best value of the chimney outlet radius (R_{To}) for the case of having maximum air velocity is obtained.

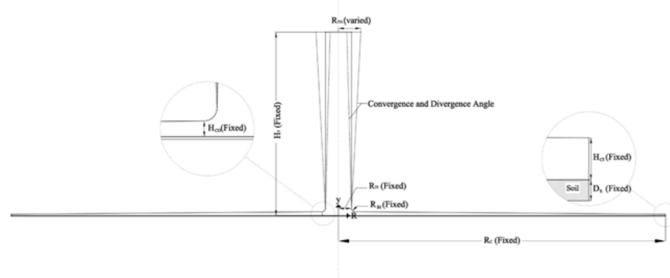

Fig. 1. Diagram of the SCPP with the various tower geometry

3. GOVERNING EQUATIONS

For the numerical simulations, the ANSYS CFX 2016 solves the conservation equations for mass, momentum, and energy using the nite volume method. These equations are presented below and the details can be found in Refs. [23,25]:

$$\text{MassConservation} : \frac{\partial}{\partial x_i}(\rho u_i) = 0 \tag{1}$$

$$\text{MomentumConservation} : \frac{\partial}{\partial x_i}(\rho u_i u_j) = 0 \tag{2}$$

$$\text{EnergyConservation} : \frac{\partial}{\partial x_i}(\rho u_i h_{total}) = \frac{\partial}{\partial x_i}(\lambda \frac{\partial T}{\partial x_i}) + u_i S_M + S_E \tag{3}$$

Where ρ is the density of air, $\{u_i; i = 1, 2, 3\}$ are the air velocity components, p is pressure, S_M is source term in the momentum equations, h_{total} is total enthalpy, λ is thermal conductivity, T is absolute temperature and S_E is source term in the energy equation [19].

4. NUMERICAL METHOD AND BOUNDARY CONDITIONS

In this study, the governing equations are discretized and solved numerically assuming symmetry flow inside the 3D computational domain (see Fig. 2) by using ANSYS-CFX code, based on finite volume procedure. For the simulation, the steady-state analysis is considered. The computational domain is divided into two parts which consisted of the air domain (containing the fluid inside the solar chimney and the solar collector) and the solid domain (containing the soil as an energy storage material). The working uid is air which is modeled as an ideal gas. The reference pressure is set as 1.0 atm. The model of the chimney is built from the origin and developed in the positive y-direction. The buoyancy model is then applied by specifying the gravity of -g in the y-direction. The heat transfer model of air domain and soil domain is total energy and thermal energy, respectively (see Table 3 for the procedure and characteristic of the numerical simulation).

The boundary conditions of this study are shown in Fig. 3. The boundary type at the inlet of collector and chimney outlet are two openings with zero relative pressure and a static temperature of 298.6 K. The thermal and velocity boundary conditions for chimney and bend junction walls are adiabatic and no-slip conditions, respectively. The boundary type at the collector is set as no-slip wall with a radiation source of 832 w/m2 and convection heat transfer coefficient of 8.5 w/m2 K. The tower axis is set as symmetry. The bottom surface of the soil domain is assumed as isothermal $T_S = 31.3°C$. The edge surface of the soil domain is assumed as an adiabatic wall. The soil axis

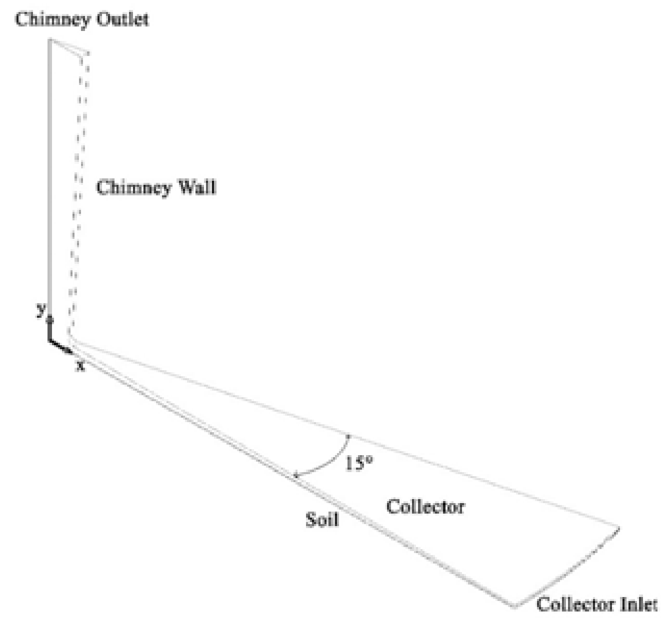

Fig. 2. 3D computational domain of SCPP

Table 3. The procedure and characteristic of the numerical simulation.

Subject	Numerical method
Computational domain	Air domain/ Solid domain
Type of modelling/Software	3-Dimensional / ANSYS-CFX
Method of analysis	Steady state analysis
Fluid characteristic	Air ideal gas
Fluid model (Heat transfer)	Total energy
Energy source term	Radiation source
Fluid model (turbulence)	Shear stress transport (SST)
Reference pressure	1.0 atm
Buoyancy model	Buoyant model
Solid Model (Heat transfer)	Thermal energy

is also set as symmetry. Eventually, the appropriate interface region is created between the collector (air domain) and the soil (solid domain). In this study, the physical characteristics of soil and air are assigned similar to those of the Manzanares prototype [4, 5, 14] and they are presented in Table 4. Also, the depth of the soil is assigned 1.0 m and the density and thermal conductivity of the soil are varied in depth based on the graph mentioned in Refs. [4, 5, 14]. The automatic mesh connection method is selected for the interface. The simulation is run for 2000 iterations; for convergence, residual type of RMS and the residual target value of 1×10-5 are set as the criteria.

5. MESH AND GRID CHARACTERISTIC

ICEM CFD software is used for grid generation. The ICEM CFD Hex-Mesher method is used to discretize the computational domain. Meshing for all domains is shown in Fig. 4. To perform the grid independency analysis, we considered four different grid

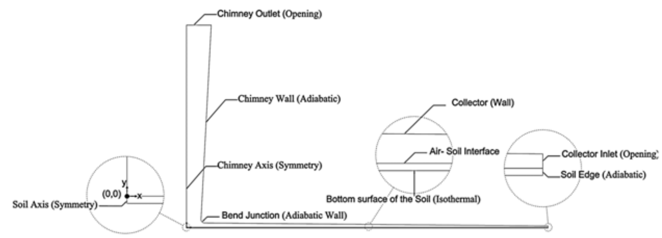

Fig. 3. Boundary conditions of this study.

Table 4. Soil and air physical properties of the Manzanares prototype [4, 5, 14].

Property	Soil	Air
Density (kg m^{-3})	UDF (variable with depth)	1.18
Thermal conductivity (w $m^{-1}K^{-1}$)	UDF (variable with depth)	0.0271
Expansion coefficient (K^{-1})	-	0.0033
Viscosity ($kgm^{-1}s^{-1}$)	-	1.83×10^{-5}
Specific Heat ($jkg^{-1}K^{-1}$)	840	1004
Pressure (Pa)	-	1

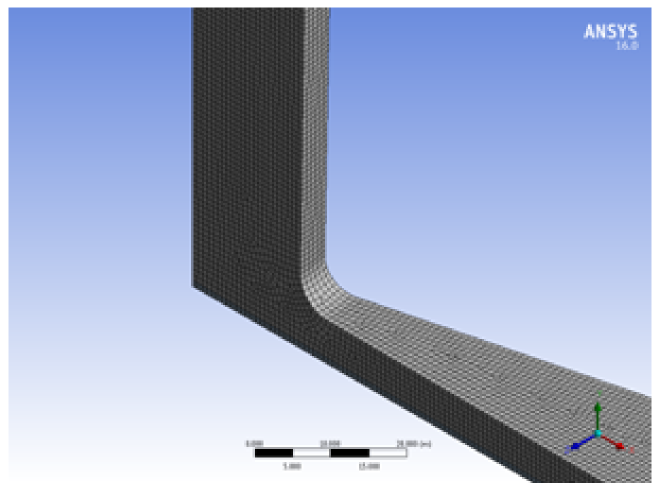

Fig. 4. Meshing for the all domains of SCPP.

sizes of 92852,152893, 273018 and 443204 meshes. The judging criterion is the average of air velocity at the wind turbine inlet (by considering the turbine pressure difference). The average air velocities obtained for four mentioned grid sizes are 7.99, 8.13, 8.54 and 8.60 m/s, respectively. The obtained air velocities show that the results for third and fourth mesh grid sizes are approximately the same. So a grid size of 273018 meshes is chosen for all the simulations. The percentage error of the averegae air velocity related to the finer grid is also presented in Table 5.

6. VALIDATION

Due to the fact that the Manzanares power plant was the first successful experimental prototype in the world, it is also replicated in this work to validate the results. To this aim, some boundary conditions and environmental characteristics, such as air properties and soil features (e.g. thermal conductivity and apparent density), as well as the efficiency of the wind turbine, are reproduced through analytical correlations, from the analysis of the experimental data on Manzanares prototype, throughout the

Table 5. Comparison of the average of air velocity variations in the tower entrance (turbine inlet) for various grid sizes.

Model Number	No.1	No.2	No.3	No.4
Number of meshes	92852	152893	273018	443204
Average of air velocity at turbine inlet (m/s)	7.99	8.13	8.55	8.65
Persentage error related to model No.4	7.60%	6.00%	1.15%	0

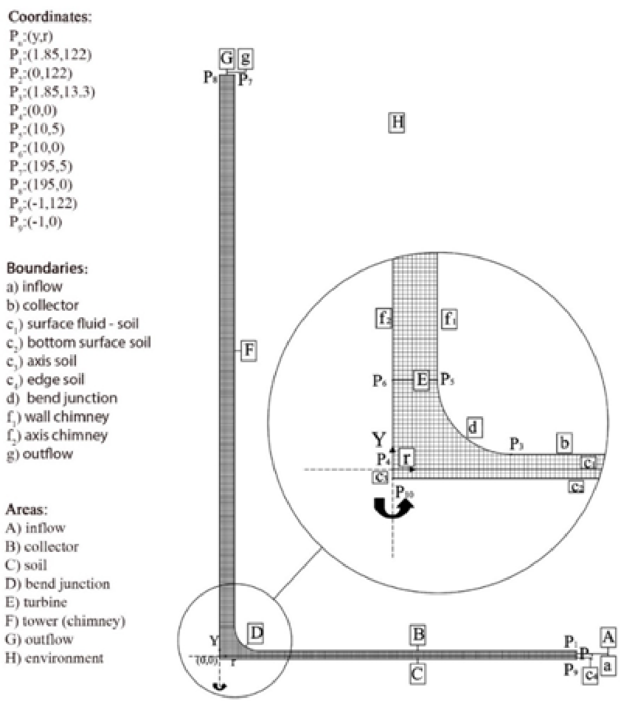

Fig. 5. Areas, boundaries, and coordinate system of the Manzanares prototype.

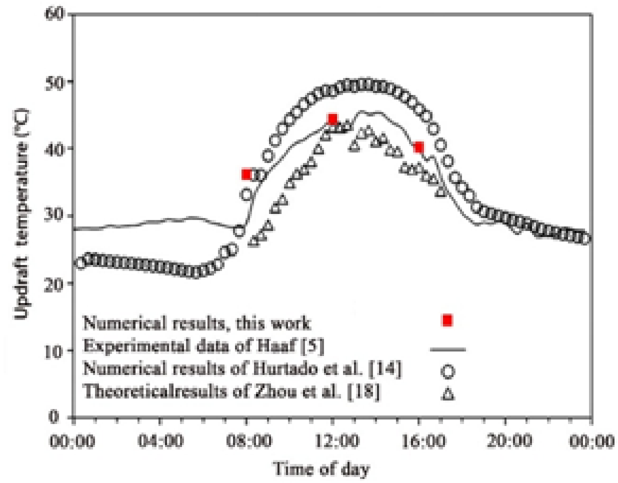

Fig. 6. Updraft temperature of air at the wind turbine inlet in Manzanares prototype.

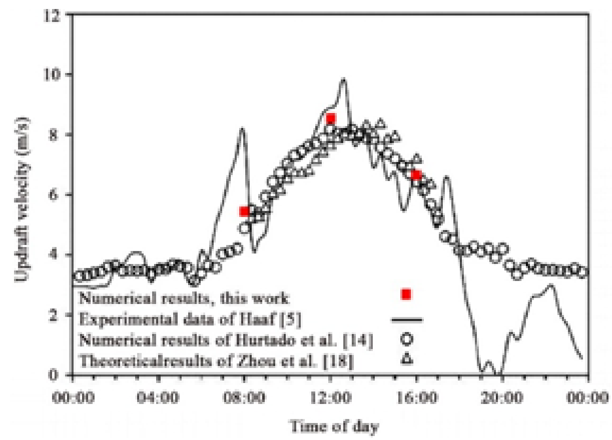

Fig. 7. Updraft velocity of air at the wind turbine inlet in Manzanares prototype.

day 2 September, 1982 [4,5]. The geometry of the Manzanares prototype is shown in Fig. 5. The system geometry consists of a chimney with 200 m height and 5 m radius surrounded by a collector with 120 m radius and 1.85 m height (see Table 6) [4,5,26]. The physical characteristics of soil and air are given in Table 2. Since the pressure drop exploited by wind turbine causes the established air velocity decreases, it can be concluded that $U_B = [(2(1-f)\Delta P_{sc})/(\rho_B)]^(1/2)$, where, $f = 2/3$ is an exploitation factor of the pressure drop (see Refs. [5,14]), ρ_B is the air density at the chimney base, ΔP_{sc} is the pressure drop inside the chimney, and U_B is the updraft air velocity at the chimney base. The current simulation and its numerical results (average air temperature and velocity at the wind turbine inlet) are presented and compared with the experimental data of Haaf [5], theoretical results of Zheu et al. [18], and numerical results of Hurtado et al. [14] at three deferent times in a day, i.e. 8 am, 12 noon and 16 pm, 14th September (see Figs. 6- 7). In addition, the percentage errors between the present simulation and the experimental data of Haaf [5], and the numerical results of Hurtado et al. [18] are calculated and tabulated in Table 7. The results given in Figs. 7 and 8 and Table 7 show a good agreement with those data reported by the Refs [5,14,18].

7. RESULTS AND DISCUSSIONS

After performing the validation for Manzanares prototype, the procedure for simulation on obtaining the suitable form for the chimney of the mentioned 1.0 MW SCPP with the main geometry given in Table 1, can be started. The results of this simulation are presented in this section. Fig. 8 shows the air velocity contours for the different chimney's geometries considered in this study, i.e. the basic form (cylindrical case), form 1 (-0.50° convergence angle – the worst case) and form 7 (+3.01○ divergence angle – the best case). It can be concluded from the figure that the maximum and average updraft air velocities at the base of the tower are low when the angle of the vertical wall of the tower is convergent. For example, these values for the form 1 are around 23.33 m/s (max) and 13.51 m/s (average). However, in the cylindrical form (basic form), the maximum and average updraft air velocities at the base of the tower are around 26.70 m/s and 15.66 m/s, respectively.

In addition, the results revealed that by changing the cylindrical form to the truncated cone with the divergence wall, the maximum and average updraft air velocities at the base of the

Table 7. The percentage deviation between numerical results of this work and experimental results of Manzanares prototype.

Item	Time of day	Experimental data of Haaf [5]	numerical results of Hurtado et al. [14]	Numerical results, present work	Percentage deviation to Experimental data of Haaf
Updraft temperature (°C)	8 am	29	33.14	36.20	24.80%
	12 noon	44	48.51	44.40	0. 90%
	16 pm	40	45.79	40.23	0.57%
Updraft velocity (m/s)	8 am	6.31	4.82	5.27	12.69%
	12 noon	8.84	8.12	8	10.50%
	16 pm	6.67	6.40	6.33	5.09%

Table 6. Dimensions of the Manzanares prototype [4,5,26].

Geometric parameters	Values
Height of the tower (chimney) (HT)	194.60 m
Radius of the tower (RT)	5.08 m
Height of the collector (HC)	1.85 m
Radius of the collector (RC)	122 m

tower increased regularly. However, this increment stops when the divergent angle becomes larger than +3.01° in form 7. The maximum and average updraft air velocities at the base of the tower (in form 7) are around 38.46 m/s and 22.52 m/s, respectively. So, the chimney geometry based on form 7 could be the suitable case of the simulation.

ig. 9 illustrates the pressure contours inside the SCPP chimney with the basic form, form 1, and form 7. The figure shows that, by an increase in chimney outlet diameter (or increasing divergent angle), the pressure difference is increased at the base of the chimney (which occurs at near the bend junction in chimney inlet). So, it could be concluded that, if the pressure difference is high, the velocity of the air will be high. In addition, the results show that the pressure difference between the collector inlet and the base of the chimney (chimney inlet) for the form 7 is the highest value (around 1150 Pa). This issue is one of the reasons of increasing the updraft velocity inside the chimney for form 7.

Fig. 10 shows the updraft air velocity distribution for the different tower forms (basic form and forms 1, 2, 7, and 9) at $y = 11$ (the elevation of the wind turbine). It can be seen from the figure that the minimum and maximum velocity occurs at the tower's centerline and near the tower wall, respectively, while the lowest flow rate values are occurred in form 1 by -0.50° convergent angle (The maximum and average updraft air velocities at the base of this tower are around 23.33 m/s and 13.01 m/s, respectively). Then, the cylindrical form (basic form) has lower flow rate values in comparison with cases (The maximum and average updraft air velocities at the base of this tower are around 26.70 m/s and 15.66 m/s, respectively). So, the highest flow rate values are occurred in form 7 by 3.01° divergent angle (The maximum and average updraft air velocities at the base of this tower are around 38.46 m/s and 22.52 m/s, respectively). Also, the form 9 (3.50 ° divergent angle) has lower flow rate values to form 7. Finally, the best value of the chimney outlet radius is obtained at form 7 (i.e.$R_(To) = 34.15$m in form 7).

It is worth to mention that, by implementing this design procedure to the defined 1.0 MW SCPP in Table 1, the average updraft air velocity increases from 15.66 m/s for the basic form to the value of 22.52 m/s for the form 7, (i.e. around 43.81% increment).

8. CONCLUSIONS

The present work investigates numerically the influence of geometric variation of the tower on the performance of a typical 1.0 MW SCPP with predetermined tower height, collector diameter, collector inlet opening, collector outlet height and chimney (tower) inlet opening. According to the importance of the kinetic power of the hot air (updraft air velocity inside the chimney) on power generation of SCPP, This article aims to propose an approach to increase the air velocity by considering the various forms of the chimney without changing the main dimensions of SCPP such as tower height and collector geometries. The desired geometrical parameters in this investigation, are tower convergence and divergence angles of the tower wall. The variation of these parameters on increasing the updraft airow velocity inside the SCPP chimney is highlighted. For the numerical simulations, a commercial CFD code solver based on the finite volume method is implemented. In this study, 15 forms of chimney wall based on a logical instruction (from a cylindrical form to a convergent and divergent form) are simulated. The discussed results included the maximum and average updraft air velocities inside the tower. After implementing the procedure, a divergence angle of the chimney wall is simulated. The results illustrate that the geometric variations in components (such as collector and tower) of one SCPP can have a significant effect on the airflow velocity and, hence, increase the amount of energy produced. In fact, by creating a divergent angle on the solar chimney wall, the fluid flow velocity increases. Therefore the form 7 (with +3.01° of divergence angle of chimney wall) has the highest updraft air velocity, which is an important factor on wind turbine power generation. It is also worthy to not that, the average updraft air velocity increases from 15.66 m/s for the basic form to the value of 22.52 m/s for the best form (form 7), (i.e. around 43.81% increment). The results also revealed that the pressure difference between the collector inlet and the base of the chimney (chimney inlet) for the form 7 is the highest value (around 1150 Pa). This issue is one of the reasons of increasing the updraft velocity inside the chimney for the form 7.

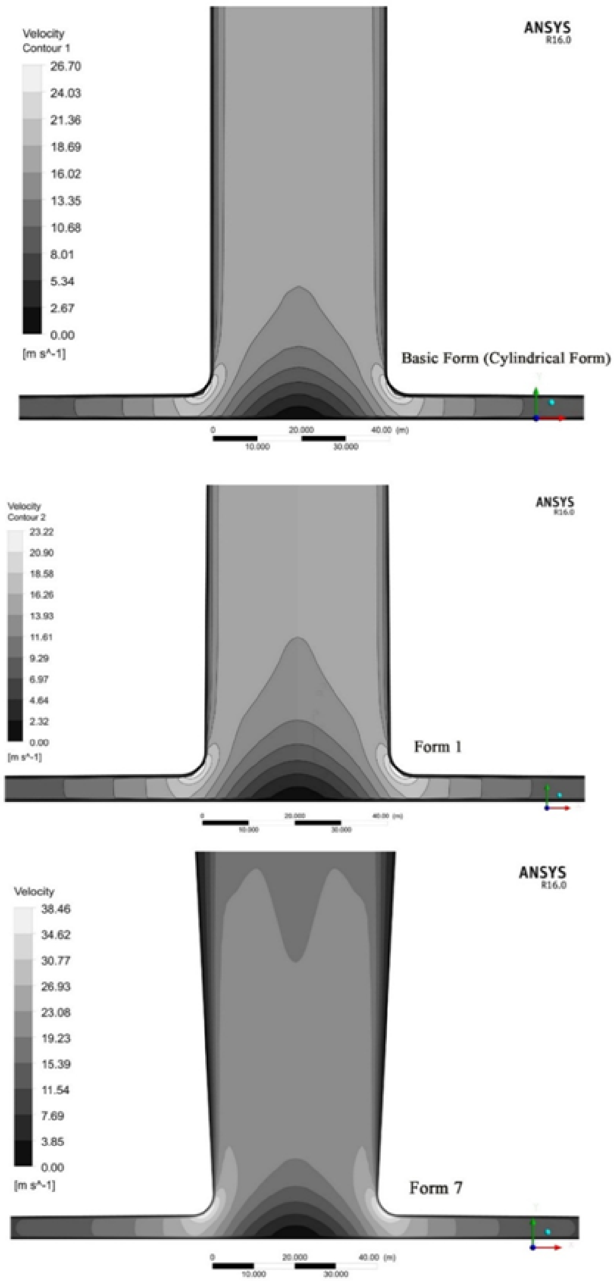

Fig. 8. Velocity contours for basic form (cylindrical case), form 1 (convergence angle) and form 7 (optimal divergence angle).

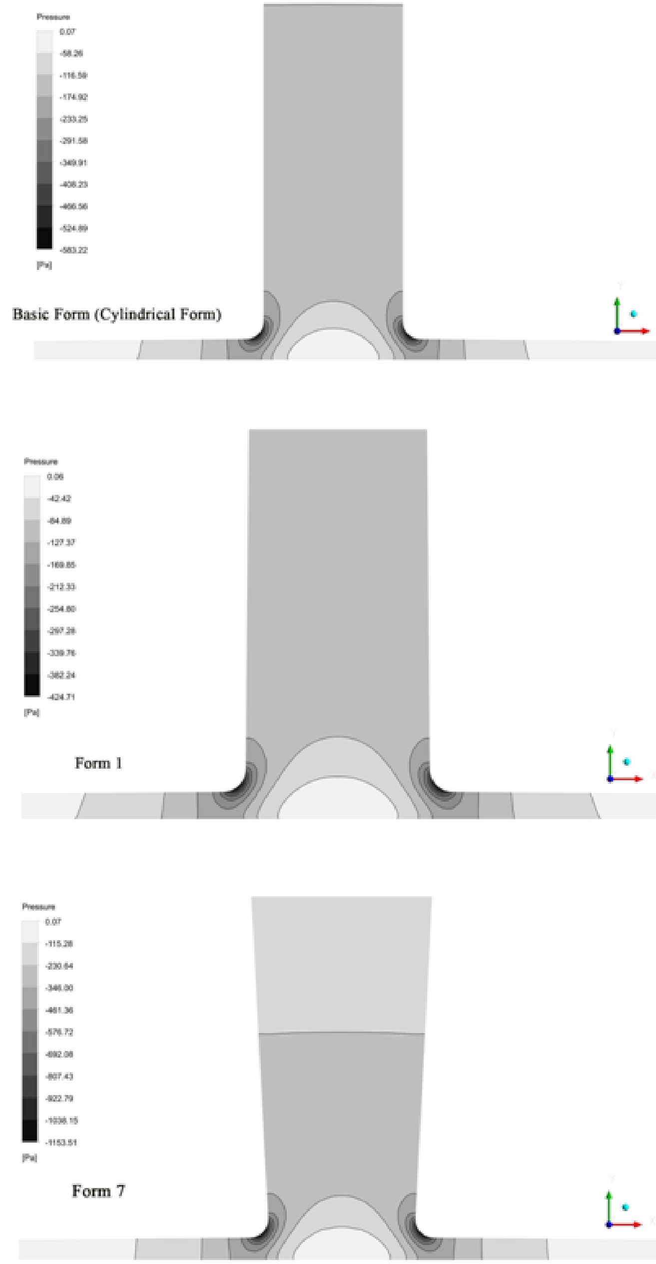

Fig. 9. Pressure contours for basic form (cylindrical case), form 1 (convergence angle) and form 7 (optimal divergence angle) at the chimney inlet.

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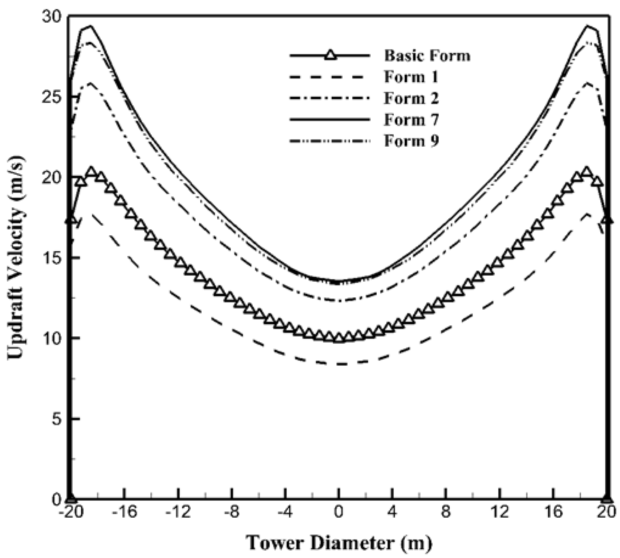

Fig. 10. The updraft air velocity distribution for the different tower forms (basic form and forms 1, 2, 7, and 9) at $y = 11$ (the elevation of wind turbine).

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