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CFD simulation of the effect of geometrical parameters of the tower-chimney on the flow behavior in a solar chimney

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***Abstract*—The solar chimney power plant is an economic device that used solar radiation to produce electricity. It converts internal energy of the air into mechanical energy and then to electrical energy. This study aims to investigate CFD simulation of the influence of the tower-chimney geometrical parameters on the flow inside a solar chimney using commercial software Ansys Fluent. Indeed, the variation of the height and the radius of the tower chimney are analyzed. A 2D axisymmetric turbulent model is adopted, considering Manzanares prototype.**

The mathematical model (Naviers-Stokes and Energy Equations) are solved using the Finite Volume Method. A standard K-ε turbulent model is used. The main results show that the height and the radius of the tower chimney affect the flow in the solar chimney. Also, the mass flow rate is significantly influenced by geometrical parameters of the tower chimney.

***Keywords*— Solar chimney, geometrical parameters, CFD, k-ε model, natural convection**

I. INTRODUCTION

During the last decades, the use of renewable energy to produce electrical power becomes a challenge in order to reduce pollution and protect environment. The Solar energy is clean source of energy which is available everywhere. The solar chimney power plant is device that converts solar energy into electrical energy using wind turbines. It is very important to optimize these systems to ensure optimum conditions of exploitation of solar energy.

In 1903, Cabanyes was the first who proposed the SCPP concept [1]. In 1931, Gunther [2] published a paper presented a description a description of a solar chimney power plant. Haaf et al. [3] conducted theoretical investigation on the famous prototype of Manzanares, spain. In order to improve the performance of SCPP, extensive research has been carried out in this field. Pastohr et al. [4] applied CFD simulation to Manzanares prototype with the aim of obtaining a more detailed analysis of both the operating mode and the efficiency of the system. Von Backström et al. [5] analysed experimentally the pressure drop in a tall solar chimney with internal bracing wheels, to obtain the bracing wheel loss coefficient. Lebbi et al. [6-7] interested in the effects of meteorological and geometrical parameters on the thermo-hydrodynamic flow in the solar chimney. They obtained that the flow behaviour is affected by the tower chimney dimensions.The numerical simulation conducted by Chergui et al. [8] on the laminar heat transfer flow in the solar chimney revealed that the maximum value of velocity appears at the tower-chimney inlet. Larbi et al. [9] examined the solar chimney power plant performance expected to provide the remote villages located in Algerian south-western region with electric power. Bouabidi et al. [10] conducted numerical and experimental investigation on both the effect of the form the tower chimney and the divergent collector on the performance of solar chimney. They obtained that the form of the tower chimney and the collector divergence affects the air flow behaviour inside the chimney. The analysis performed by Arce et al. [11] on the air flow in the solar chimney power plant showed that temperature gradient occurred in the collector affects the velocity of the flowing air. Chitsomboon [12] developed mathematical model of the SCPP system. Their results indicated that the convergent chimney features the same performances of the standard chimney. Sangi et al. [13] investigated theoretically by developing a mathematical model of the SCPP and numerically using commercial software Fluent to simulate Manzanares SCPP. They revealed that mathematical

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model and numerical analysis are in good agreement with experimental data. Morteza [14] studied numerically the effects of pressure drop across turbine and the solar radiance on the performance of a SCPP, which is expected to produce electric power to a city located in the southern region of Iran. They found that the pressure drop and the solar radiation affect the efficiency. Besides, they obtained that the SCPP can provide up to 40-200 kW of power, depending on the season. Kasaeian et al. [15] conducted numerical and experimental investigation of the SCPP based on their experimental prototype. They showed that the SCPP efficiency is significantly affected by geometrical parameters. Hu et al. [16] used commercial code Fluent to examine the effects of divergent chimney of SCPP. Different cases were investigated. They varied the chimney exit over entrance and the divergent angle of the chimney. Their results revealed all the studied parameters affect the SCPP performance. Then, Kebabsa et al. [17] studied numerically thermo-hydrodynamic behavior of an innovative solar chimney, named sloped collector entrance SCPP. They obtained that the modified collector entrance design improve significantly the SCPP performance. Daimallah et al. [18] carried out numerical investigation on the effect of the height and the radius of the collector on the flow behavior in small solar chimney. Their results show that the mass flow rate is enhanced by about 27% for Rc = 12.5m and Hc = 0.25m. Kebabsa et al. [19] used CFD to simulate a novel concept of tower solar chimney which consists of annular tower solar chimney. They found that the total improvement in power output reaches 32% for the annular tower solar chimney. Nasraoui et al. [20] conducted a comparison between three models; conventional collector, double-pass collector with parallel flow and double-pass collector with counter flow. Their results revealed that the double-passes counter flow collector enhances the collector efficiency by 28% comparing to the conventional collector. Daimallah et al [21, 22] analysed the influence of the radius ratio Rt* = Rtout/Rtinlet and the height of the tower-chimney, on the flow behavior inside the SCPP of Manzanares. The obtained results indicate that mass flow rate is increased by about 58.23% for the divergence of the tower-chimney.

Elsayed [23] conducted numerical simulation using the CFDRC code to analyse the integration of swirl guide blade into the collector. Their results revealed that the average velocity at the chimney entrance and system power is increased by 115.1% and 30.2% using eight guide vanes, respectively.

In this paper, we are interested in the study the flow behaviour inside a SCPP. Particularly, the chimney dimensions (radius and height) on the local characteristics such as the velocity, mass flow rate and temperature are presented and discussed.

II. MATHEMATICAL FORMULATION

A. Physical model

Figure 1 shows the physical model geometry of the studied solar chimney. This design has a collector radius (Rc =120m), collector height entrance (Hc = 1.7m), tower chimney height (Ht = 195m) and tower chimney radius (Rt = 5m). The values of $Rt^*=R/R_t$ and $Ht^*=H/H_t$ are varied as shown in Table 1.

TABLE I DIFFERENT CONFIGURATIONS OF THE SCPP

Ht(m)	Rt(m)	Ht^*	Rt^*
195	5	1; 0.5; 0.25	1; 1.25 ;1.5;1.75; 2

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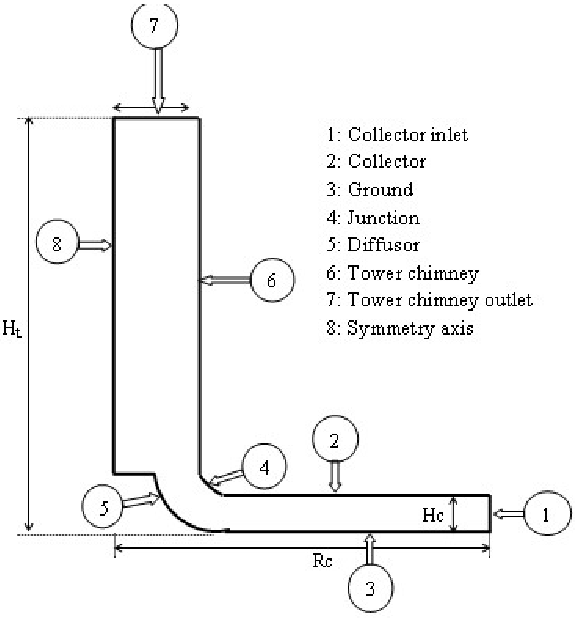

Fig. 1 Physical model of the problem

B. *Governing equation*

The airflow through the solar chimney power plant is prescribed by two-dimensional turbulent natural convection in cylindrical coordinates. The fluid is incompressible and satisfies the Boussinesq approximation, which implies that the density variation with temperature is negligible except in the motion equation for the buoyancy term. The governing equations that describe the flow are given by,

Continuity equation

$$\frac{\partial(\rho u)}{\partial x}+\frac{1}{r}\frac{\partial(r\rho v)}{\partial r}=0 \qquad (1)$$

Momentum equations

$$\frac{\partial(\rho uu)}{\partial x}+\frac{1}{r}\frac{\partial(r\rho uv)}{\partial r}=-\frac{\partial p}{\partial x}+2\frac{\partial}{\partial x}\left[(\mu+\mu_t)\frac{\partial u}{\partial x}\right]+\frac{1}{r}\frac{\partial}{\partial r}\left[(\mu+\mu_t)r\left(\frac{\partial u}{\partial x}+\frac{\partial v}{\partial r}\right)\right]+(\rho-\rho_0)g \qquad (2)$$

$$\frac{\partial(\rho uv)}{\partial x}+\frac{1}{r}\frac{\partial(r\rho vv)}{\partial r}=-\frac{\partial p}{\partial r}+\frac{\partial}{\partial x}\left[(\mu+\mu_t)\left(\frac{\partial v}{\partial x}+\frac{\partial u}{\partial r}\right)\right]+2\frac{1}{r}\frac{\partial}{\partial r}\left[(\mu+\mu_t)r\frac{\partial v}{\partial r}\right]-\frac{2(\mu+\mu_t)v}{r^2} \qquad (3)$$

Energy equation

$$\frac{\partial(\rho uT)}{\partial x}+\frac{1}{r}\frac{\partial(r\rho vT)}{\partial r}=-\frac{\partial}{\partial x}\left[\left(\frac{\mu}{\Pr}+\frac{\mu_t}{\sigma_t}\right)\frac{\partial T}{\partial x}\right]+\frac{1}{r}\frac{\partial}{\partial r}\left[\left(\frac{\mu}{\Pr}+\frac{\mu_t}{\sigma_t}\right)r\frac{\partial T}{\partial r}\right] \qquad (4)$$

Turbulent kinetic energy equation

$$\frac{\partial(\rho ku)}{\partial x}+\frac{1}{r}\frac{\partial(r\rho kv)}{\partial r}=\frac{\partial}{\partial x}\left(\left(\mu+\frac{\mu_t}{\sigma_k}\right)\frac{\partial k}{\partial x}\right)+\frac{1}{r}\frac{\partial}{\partial r}\left(r\left(\mu+\frac{\mu_t}{\sigma_k}\right)\frac{\partial k}{\partial r}\right)+G_k+\beta g\frac{\mu_t}{\sigma_t}\frac{\partial T}{\partial x}-\rho\varepsilon \qquad (5)$$

Dissipation of kinetic energy equation

$$\frac{\partial(\rho\varepsilon u)}{\partial x}+\frac{1}{r}\frac{\partial(r\rho\varepsilon v)}{\partial r}=\frac{\partial}{\partial x}\left(\left(\mu+\frac{\mu_t}{\sigma_\varepsilon}\right)\frac{\partial\varepsilon}{\partial x}\right)+\frac{1}{r}\frac{\partial}{\partial r}\left(r\left(\mu+\frac{\mu_t}{\sigma_\varepsilon}\right)\frac{\partial\varepsilon}{\partial r}\right)+G_kC_{1\varepsilon}\left(\frac{\varepsilon}{k}\right)-C_{2\varepsilon}\rho\frac{\varepsilon^2}{k} \qquad (6)$$

Where: $\beta g\frac{\mu_t}{\sigma_t}\frac{\partial T}{\partial x}$ represents the effect of buoyancy;

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μ_t is the eddy viscosity, expressed by: $\mu_t = \frac{\rho C_\mu k^2}{\varepsilon}$

G_k is the turbulence kinetic energy generation.

ρ_0 is the density of ambient air (kg/m^3).

C. Boundary conditions

- The boundary conditions for the computational domain are summarized in Table 2

TABLE II BOUNDARY CONDITIONS

Place	Type	Description
Centreline	Axis	Symmetry
Ground	wall	$250\ W/m^2 \leq Q \leq 1000\ W/m^2$
Collector	wall	T= 300 K
Tower	wall	$Q = 0\ W/m^2$
Collector inlet	Pressure inlet	Gauge total pressure=0 Pa Turbulent intensity= 5% $T = T_0 = 300K$
Chimney Outlet	Pressure outlet	Gauge pressure=0 Pa Turbulent intensity= 5% Backflow turbulent viscosity ratio=4 Backflow temperature $T=T_0 = 300K$

III. NUMERICAL METHODOLOGY

III.1 Numerical procedure

All steps of numerical simulations of air flow in the SCPP were performed by Ansys Fluent. Modelling the geometry, flow domain and generating mesh were carried out using Gambit and solving the governing equations was conducted by Ansys Fluent. The finite volume method and the SIMPLE algorithm have been used to solve the flow governing equations (1)-(6). The second order upwind scheme is used to discretize the convective terms. The iterative solution is converged when the residuals across all nodes are less than 10^{-6}.

III.2 Mesh generation

Generating a high-quality mesh is an essential step in computational fluid dynamic (CFD) simulations. A structured non-uniform grid with a more significant concentration on the inlet-outlet and junction regions was used. The optimum number of mesh elements is determined by performing a mesh independence test. The data of the mesh independence test are shown in figure 2. We adopt a (48X400) cells throughout the calculation domain since it has shown a negligible variation with a more refined grid.

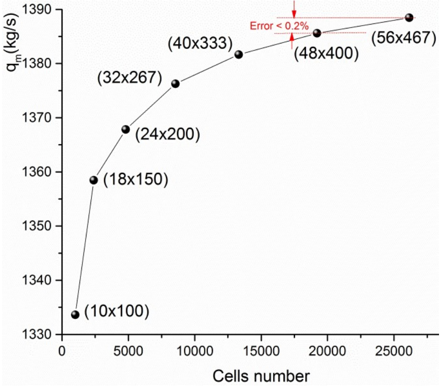


Fig.2 Mesh independence study

III.3 Validation

In order to assess validation of numerical results, values of velocity along the collector were compared with the values of velocity obtained by Pastohr et al. [5] considering the prototype of Manzanares as a model. As shown in figure 3, the obtained results indicate a good agreement between our results and those of Pastohr et al. [5].

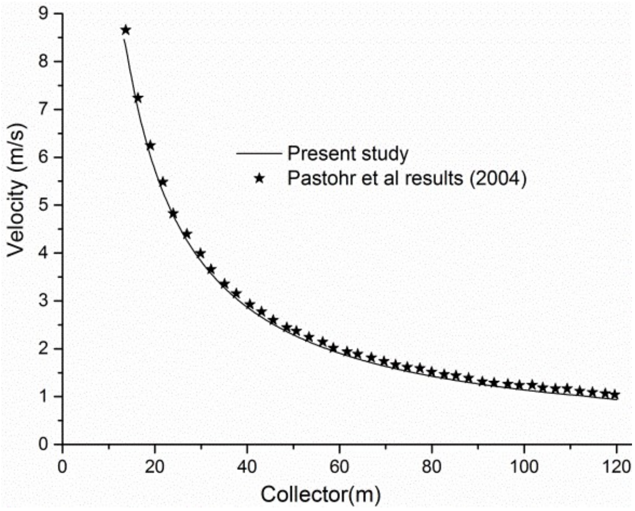
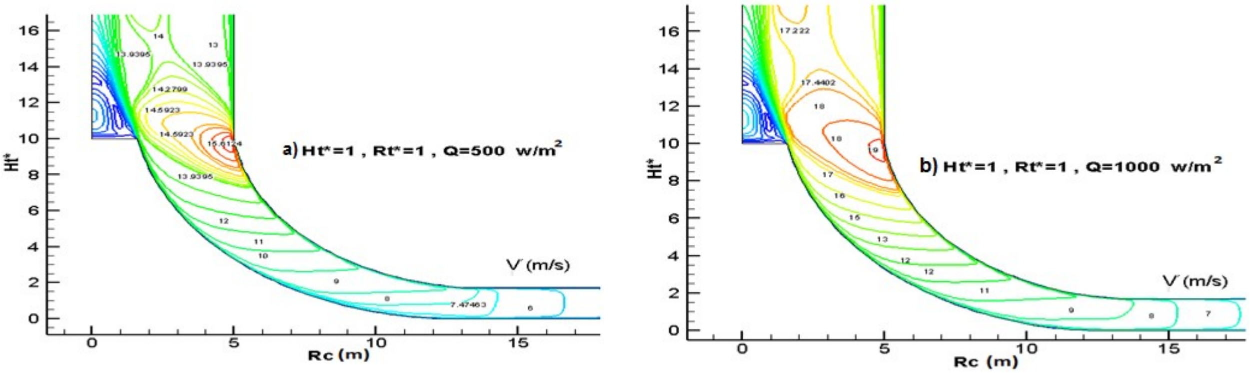


Fig. 3 Evolution of velocity profile along the collector at x = 0.85m

IV. RESULTS AND DISCUSSION

IV.1 Effect of geometrical parameters on the velocity contours for Ht= 1*

Figure 4 (a-d) illustrates the velocity contours for various values of radius ratio Rt* and solar radiation Q. It appears clearly that velocity increases versus the radius ratio Rt* and solar radiation. At the tower chimney entrance velocity reaches the value of 20.67 m/s for Rt* =1.5 and Q = 1000 W/m².



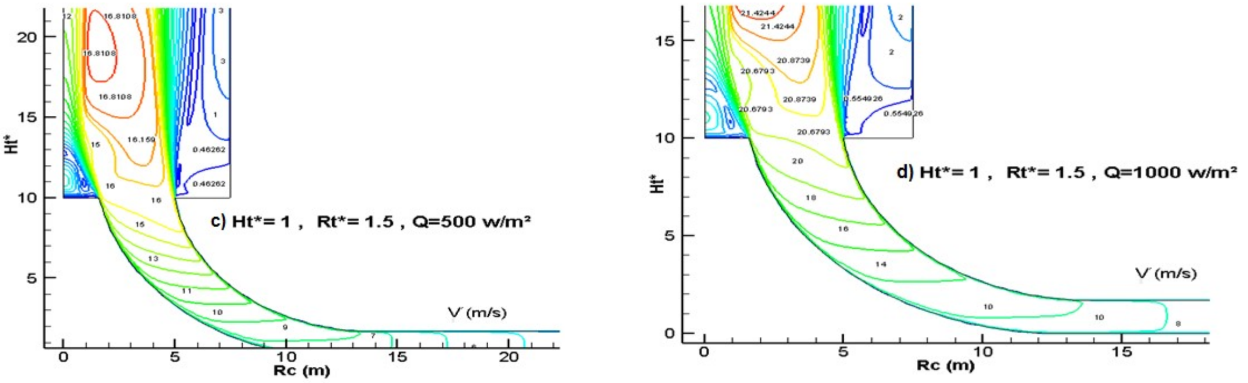


Fig. 4(a-d) Development of velocity contours for various Rt* and Q for Ht* = 1

IV.2 Effect of geometrical parameters on the velocity contours for Ht= 0.5*

The analysis of the obtained results shown on figure 5 (a-d) indicate that velocity increases versus the radius ratio Rt* and solar radiation Q. A maximum velocity is recorded at the entrance of the tower chimney. Indeed, velocity increases from 12.39 m/s for Rt* = 1 and Q = 500 W/m² to 23.28 m/s for Rt* = 2 and Q = 1000 W/m².

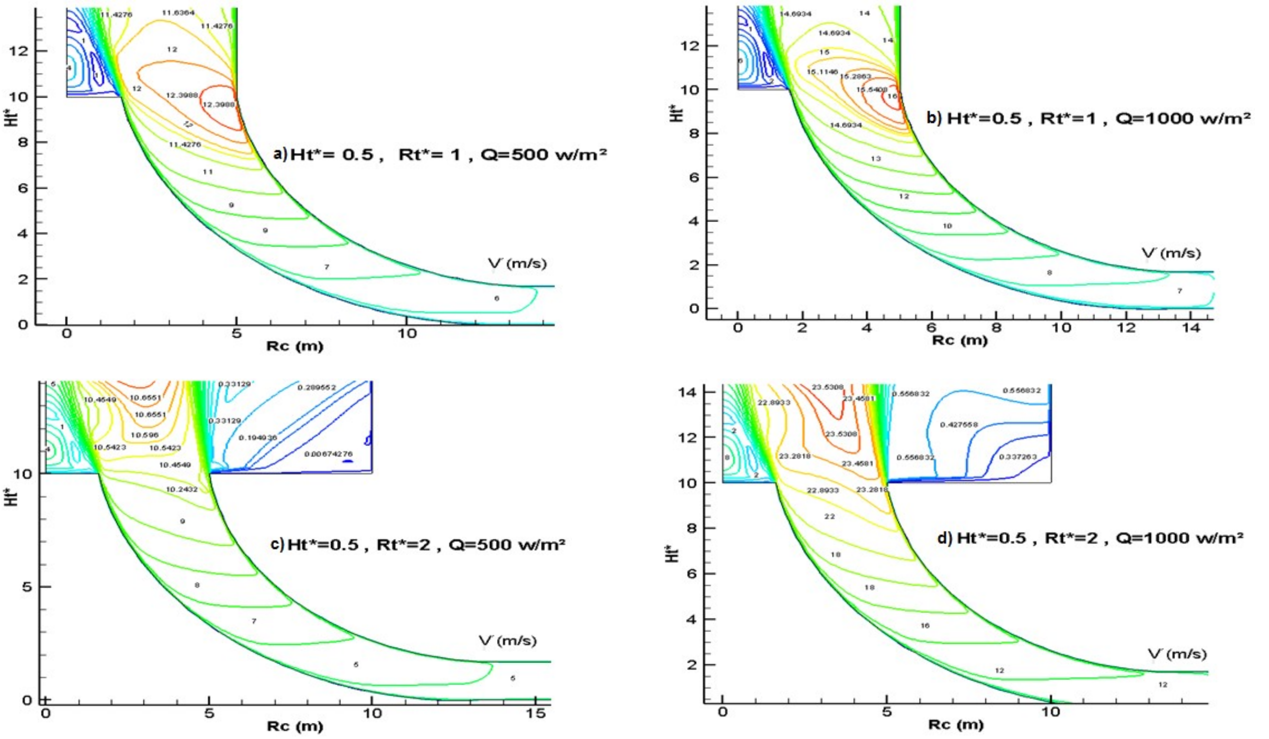


Fig. 5(a-d) Development of velocity contours for various Rt* and Q for Ht* = 0.5

IV.3 Effect of geometrical parameters on the velocity contours for Ht= 0.25*

The results depicted in figure 6(a-d) the velocity contours for various Rt* and Q for Ht* =0.25. We observe the same evolution of the velocity contours comparatively to the previous studied cases. We note that velocity increases versus the radius ratio Rt* and solar radiation Q. The velocity reaches 13.87 m/s for Rt* = 1.5 and Q = 1000 W/m².

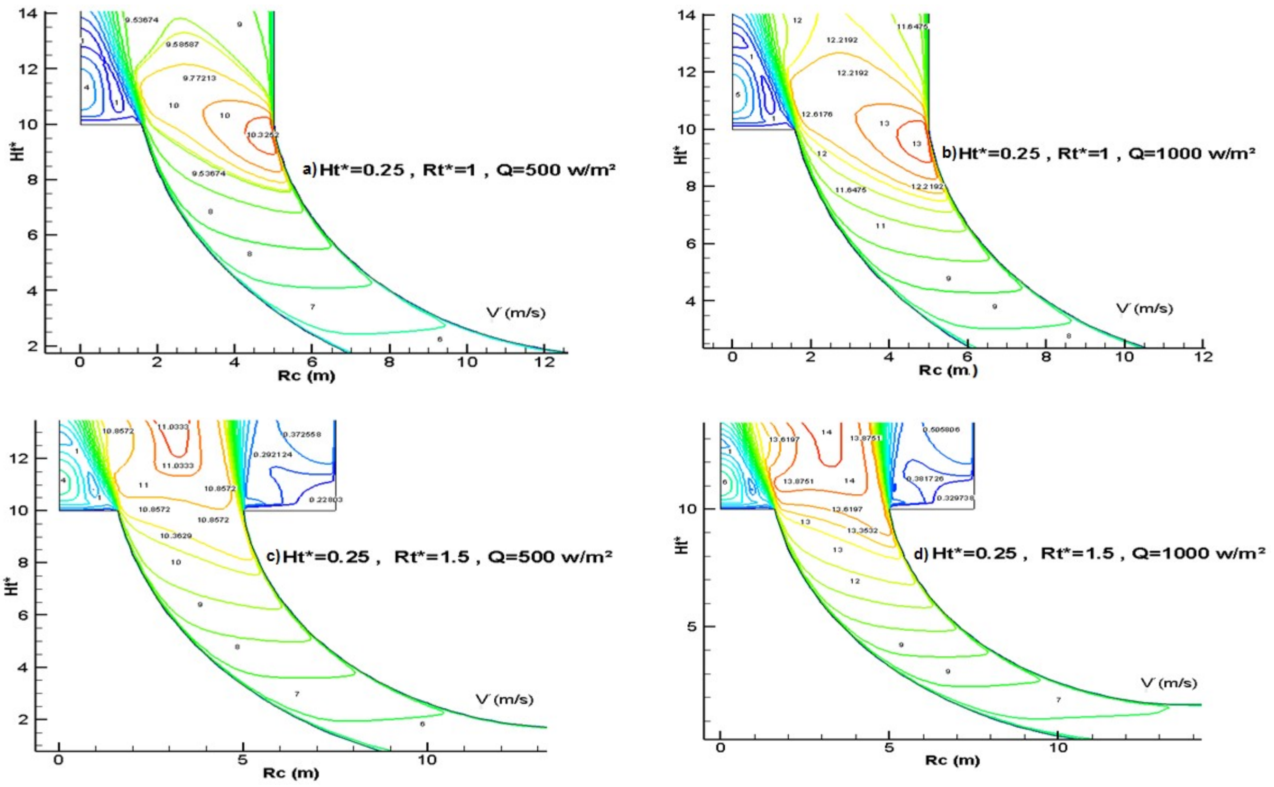
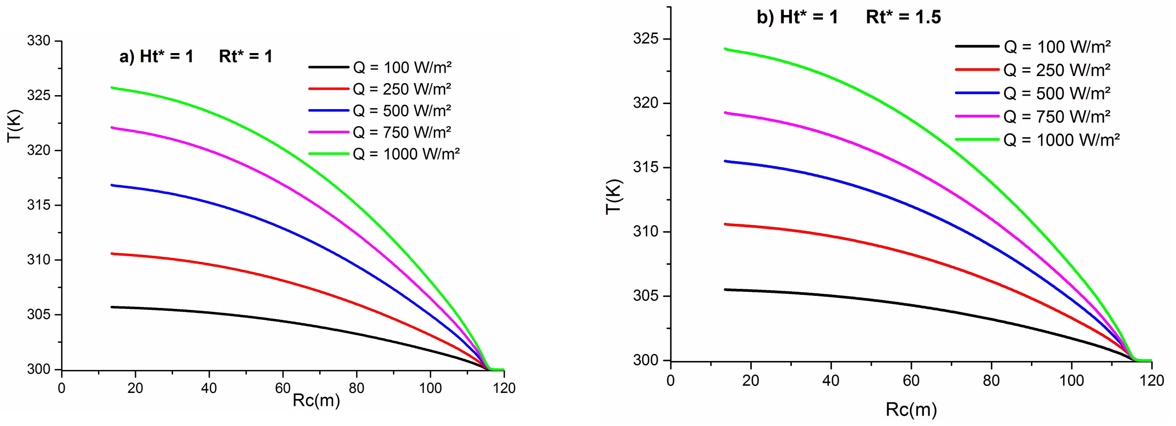


Fig.6(a-d) Development of velocity contours for various Rt* and Q for Ht* = 0.25

IV.4 Effect of geometrical parameters on the temperature field

Figure 7 (a-f) shows the variation of temperature along the collector at x = 0.85m for various radius ratio Rt*, solar radiation Q and Ht*. It appears clearly that temperature increases along the collector and it depends on geometrical parameters (Ht* and Rt*) and the solar radiation Q. We note a high value of temperature for Ht* =0.25 and Rt* =1. Indeed, temperature reached the value of 345.55 K for Q = 1000 W/m².



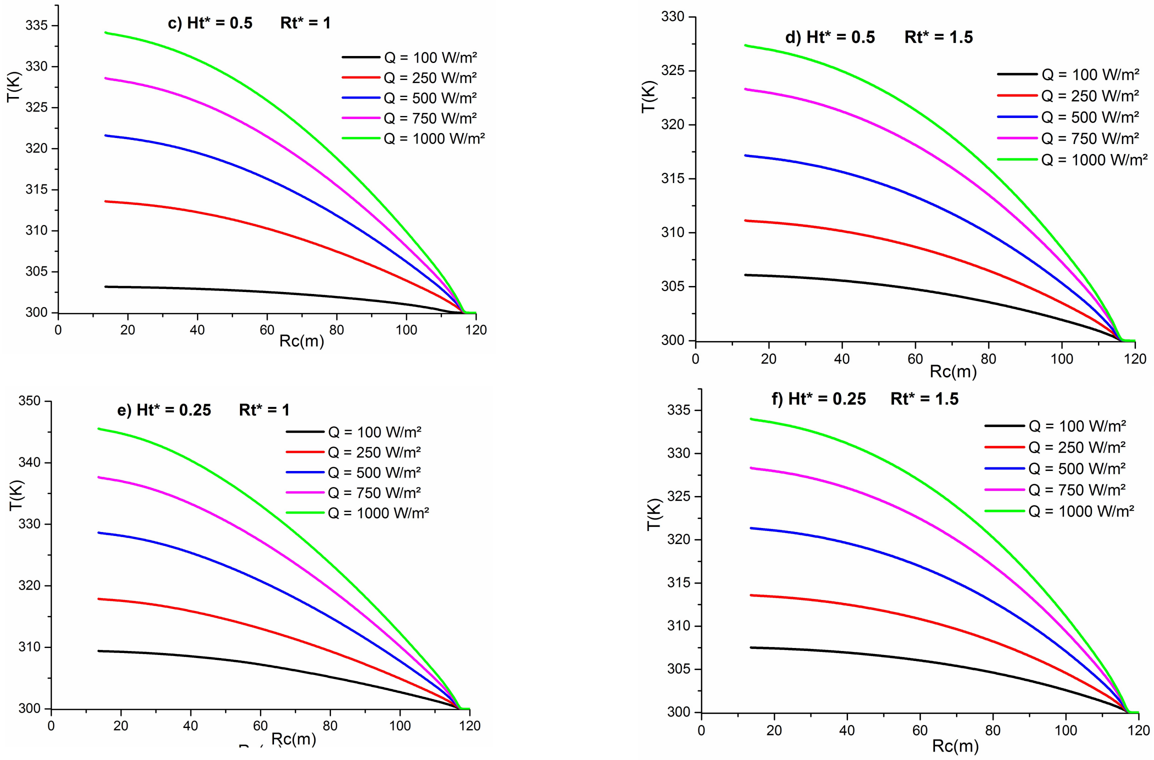


Fig. 7 (a-f) Evolution of temperature along the collector at x = 0.85m for various Rt*, Ht* and Q

IV.5 Effect of geometrical parameters on the mass flow rate

Figure 8(a-b) shows the variation of mass flow rate versus radius ratio Rt* for both various solar radiation Q and Ht*.

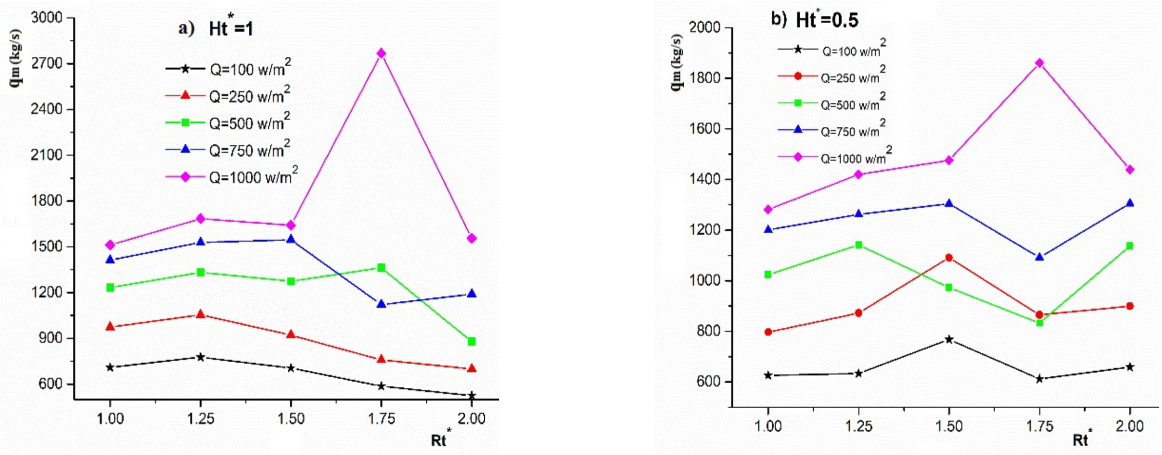


Fig. 8(a-b) Variation of mass flow rate versus Rt* for various Q and Ht*

From the results shown in figure 8(a-b), we note that mass flow rate is influenced by the radius ratio Rt*, height ratio Ht* and solar radiation Q. Il appears clearly that mass flow rate increases versus solar radiation Q and decreases versus height ratio Ht*. The height value of mass flow rate is reached for Rt* =1.5 and Ht* =1 which is 2767,889 kg/s. Indeed, the mass flow rate is improved by about 83.06%.

V. CONCLUSIONS

In this study, we investigate numerically the effect of geometrical parameters on the flow behaviour inside SCPP. The obtained results indicate that geometrical parameters influence significantly the flow behavior in the SCPP. We

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note that velocity increases along the collector and obtain that maximal value at the entrance of the tower-chimney. The variation of temperature along the collector is affected by geometrical parameters and solar radiation Q. The mass flow rate is improved by about 83.06% for Rt* =1.5 and Ht* = 1.

REFERENCES

[1] J. Lorenzo, "Las Chimneas solares: De una propuesta espanola en 1903 a de Mansanares. De Los Archivos Históricos De La Energia Solar," http://www.fotovoltaica.com/chimenea.pdf.

[2] H. Günther, In hundred years-future energy supply of the world.: Kosmos, Franckh'sche Verlagshandlung : Stuttgart, 1931.

[3] W. Haaf, K. Friedrich, G. Mayer, J. Schlaich, "Solar chimneys," Int J Solar Energy, vol. 2, pp. 141–161,1984.

[4] H.Pastohr, O. Kornadt, K. Gürlebeck, "Numerical and analytical calculations of the temperature and flow field in the upwind power plant". Int. J. Energy Research 28, 495-510, 2004.

[5] T. W. Von Backström, A. J.Gannon, "Solar chimney turbine characteristics", Solar Energy, 76 (1-3):235-41, 2004.

[6] M. Lebbi, T. Chergui, H. Boualit, L. Boutina, "Influence of geometric parameters on the hydrodynamics control of solar chimney", Int. J. Hydrogen Energy 39, 15246-15255, 2014.

[7] M. Lebbi, H. Boualit, T. Chergui, L. Boutina, A. Bouabdallah, H. Oualli, "Tower outlet/inlet radii ratio effects on the turbulent flow control in a solar chimney", Renewable Energy Congress (IREC2015), 6th International, IEEE Conference Publications, 2015. DOI: 10.1109/IREC.2015.7110859.

[8] T. Chergui , S. Larbi , A. Bouhdjar ,"Thermo-hydrodynamic aspect analysis of flows in solar chimney power plants a case study", Renew. Sustain. Energy Rev. 14, 1410–1418, 2010.

[9] S. Larbi, A. Bouhdjar, T. Chergui, "Performance analysis of a solar chimney power plant in the southwestern region of Algeria", Renew Sustain Energy Rev, 14:470-7, 2010.

[10] A. Bouabidi, A. Ayadi, H. Nasraoui, Z. Driss, M. S. Abid, "Study of solar chimney in Tunisia: Effect of the chimney configurations on the local flow characteristics", Energy & Buildings 169, 27–38, 2018. https://doi.org/10.1016/j.enbuild.2018.01.049

[11] J. Arce , M.J. Jimenez , J.D. Guzman , M.R. Heras , G. Alvarez , J. Xaman , Experimen- tal study for natural ventilation on a solar chimney, Renew. Energy 34, 2928–2934, 2009.

[12] T. Chitsomboon , "The effect of chimney-top convergence on efficiency of a solar chimney", in: Proceedings of the 13th National Mechanical Engineering Conference, Pataya, Thailand, pp. 263–268, 1999.

[13] R. Sangi, M. Amidour, B. Hosseinizadeh, "Modeling and numerical simulation of solar chimney power plants", Sol Energy, 85:829-38, 2011.

[14] B. Morteza, "Numerical simulation of a solar chimney power plant in the southern region of Iran", Energy Equip. Sys. Vol. 5; No.4, 431-437, 2017.

[15] A. Kasaeia , M. Ghalamchi, M. Ghalamchi, "Simulation and optimization of geometric parameters of a solar chimney in Tehran", Energy Convers. Manage. 83, 28–34, 2014.

[16] S. Hu, D.Y.C. Leung, J.C.Y. Chan, "Impact of the geometry of divergent chimneys on the power output of a solar chimney power plant", Energy 120, 1–1, 2017.

[17] H.Kebabsa, M. S. Lounici, M.Lebbi, A. Daimallah, "Thermo-hydrodynamic behaviour of an innovative solar chimney", Renewable Energy 145 2074-2090, 2020. https://doi.org/10.1016/j.renene.2019.07.121

[18] A. Daimallah, M. Lebbi, M.S. Lounici, L. Boutina, "Effect of Thermal Collector Height and Radius on Hydrodynamic Flow Control in Small Solar Chimney", Journal of Advanced Research in Fluid Mechanics and Thermal Sciences 71, Issue 2, 10-25, 2020. https://doi.org/10.37934/arfmts.71.2.1025

[19] H. Kebabsa, M.S. Lounici, A. Daimallah, "Numerical investigation of a novel tower solar chimney concept", Energy 214, 119048, 2021. https://doi.org/10.1016/j.energy.2020.119048

[20] H. Nasraoui, Z. Driss, H. Kchaou, "Novel collector design for enhancing the performance of solar chimney power plant", Renewable Energy 145: 1658-1671, 2020. https://doi.org/10.1016/j.renene.2019.07.062

[21] A. Daimallah, M. Lebbi, M.S. Lounici, "Mass flow rate enhancement inside a solar chimney power plant", Fourteen International Conference on Thermal Engineering: Theory and Applications, Yalova , Turkiye May 25-27, 2023.

[22] A. Daimallah, M. Lebbi, M.S. Lounici, "Effect of the tower-chimney form on the flow behavior inside a solar chimney power plant", Topical Problems of Fluid Mechanics, Prague, République Tchèque February 16-18, 2022.

[23] A. M. Elsayed , O. A. Gaheen , M. A. Aziz, "Enhancing solar chimney power plant performance through innovative collector curved-guide vanes configurations", Renewable Energy Journal volume 232, 121127, 2024. https://doi.org/10.1016/j.renene.2024.121127