# Investigation of Divergence Angle on the Performance of Solar Chimney: A Simulation Study

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***Abstract*: Solar chimneys have gained significant attention as an environmentally friendly and sustainable solution for passive ventilation and renewable energy generation. The divergence angle, which refers to the angle between the solar chimney's sidewalls as they extend upwards, plays a crucial role in determining the system's performance. This research aims to investigate the effects of divergence angle on solar chimney operation, with a focus on airflow characteristics. Computational fluid dynamics (CFD) simulations are conducted to assess the airflow patterns, velocity distribution, and pressure drop within the chimney for different divergence angles. The research findings indicate that the divergence angle significantly influences the system's performance. The study considered four basic parameters: Pressure drop, Velocity, and Turbulent Kinetic Energy and the optimized value i.e., 312 Pa, 21.5 m/s, and 61.5 J/kg is obtained at divergence angle of 5-6°. The results showed that the divergence angle of 5-6° is the best suitable for high power production for a solar chimney power plant.**

## Introduction

India has made significant strides in solar energy deployment. As of September 2021, the cumulative installed solar capacity in India exceeded 40 Gigawatts (GW) [1]. This includes both utility-scale solar projects and rooftop solar installations. India has developed several large-scale solar parks to facilitate solar energy development. The country's largest solar park, the Pavagada Solar Park in Karnataka, has a planned capacity of 2,000 megawatts (MW) and is spread over a vast area [2]. The solar energy sector in India has witnessed competitive auctions, with tariffs reaching record lows. In some cases, solar power purchase agreements have been signed at tariffs below INR 2 per kilowatt-hour (kWh), making solar energy one of the cheapest sources of electricity in the country. India has set ambitious renewable energy targets, including solar energy [3-6]. The government aims to achieve 175 GW of renewable energy capacity by 2024, out of which 100 GW is expected to come from solar power. In addition, India has a long-term target of 450 GW of renewable energy capacity by 2030, including a substantial contribution from solar.

Solar Photovoltaic (PV) Systems, Concentrated Solar Power (CSP) Plants, Solar Thermal Systems, are the key technologies for harnessing the solar energy. Solar chimneys, Solar PV systems, and CSP plants all have their unique characteristics and suitability for different applications [7-10]. Solar chimneys are still in the experimental stage and have limited operational installations, whereas solar PV systems and CSP plants have been widely deployed globally. The choice of technology depends on factors such as available land, solar resources, energy requirements, and economic considerations.

A solar chimney, also known as a solar updraft tower or solar thermal chimney, is a type of renewable energy technology that uses solar radiation to generate electricity [11]. It is a tall structure typically consisting of a large transparent collector at the base, a tall chimney, and turbines or generators at the top. The base of the solar chimney is a wide, transparent collector made of glass or other materials with high solar transmittance. The collector absorbs solar energy and heats the air underneath [12-14]. The heated air inside the collector becomes less dense and rises due to the greenhouse effect. This creates an updraft of hot air. The updraft of hot air is channelled into a tall chimney. The chimney is typically a cylindrical or conical structure that extends vertically above the collector. As the hot air raises the chimney, it passes through a series of turbines or generators installed at the top. The movement of the air drives the turbines, which generate electricity. The electricity generated by the turbines is then collected and can be used to power homes, businesses, or stored for later use [15-18].

Solar chimneys are an interesting concept for harnessing solar energy, but they are still in the experimental stage, and there are currently very few operational solar chimney power plants around the world. Further research and development are needed to optimize their efficiency, address technical challenges, and improve cost-effectiveness. There is requirement to investigate the technical feasibility of solar chimney systems by studying their design. There is also requirement to use computational modelling and simulation techniques to analyse the airflow dynamics, heat transfer, and energy conversion processes within a solar chimney system [19-23].

The divergent angle of a solar chimney refers to the angle at which the chimney widens as it extends upwards. It is an important factor in determining the efficiency of the chimney in generating airflow and therefore, in producing energy. The optimal divergent angle depends on various factors such as the height of the chimney, the temperature difference between the air inside and outside the chimney, and the wind speed in the surrounding area. The divergent angle plays a critical role in the operation of a solar chimney. As hot air rises, it creates a natural flow of air through the chimney. The divergent angle helps to increase the velocity of the rising air by reducing the pressure at the top of the chimney. This creates a suction effect, drawing in cooler air from the bottom of the chimney, which in turn increases the flow of air and energy production. If the divergent angle is too steep, it can cause turbulence and reduce the efficiency of the chimney. On the other hand, if the angle is too shallow, it can reduce the velocity of the rising air and limit the amount of cool air drawn in from the bottom. Therefore, the divergent angle should be optimized based on the specific conditions of the site and the requirements of the system. Computational fluid dynamics (CFD) simulations can be used to determine the optimal divergent angle for a particular solar chimney design. Thus, the aim of the present work is to find out the impact of divergent angle on the performance of solar chimney.

## CFD Modelling

Firstly, it is assume that the solar chimney operates under steady-state conditions, as it allows for easier analysis of the system. Secondly, we assume that the flow inside the solar chimney is incompressible, which means that the density of the fluid remains constant throughout the system except for the Boussinesq approximation [1]. To simplify the analysis of the system under examination, the atmospheric variables were steady, the air flow was homogeneous about the collector's axis, there was no heat loss to the ground, there was no friction or leaking, there was no temperature variation between the level of the water, the glass cover, or the collector's rooftop, the collector roof and glass cover had little heat capacity, and the flow was inexhaustible. The Semi-Implicit Method for Pressure-Linked Equations (SIMPLE) algorithm was applied to couple the continuity and momentum equations through pressure. For gradient and pressure discretization, least-squares, cell-based pressure staggering option (PRESTO!) method was applied; momentum, energy, turbulence kinetic energy dissipation rate, and discrete ordinates were discretized using second-order upwind methods. All thermo-physical fluid properties are assumed to be invariant except for density in the buoyancy force term; this density term can be adequately modelled by the Boussinesq approximation, which delivers faster convergence than models with fluid densities that vary as a function of temperature.

## Geometry

Abdallah Bouabid et al. (2018) investigated four types of chimney geometry: standard, convergent, divergent, and opposing. They found that the chimney design has an immediate impact on SCPP efficiency, and that the diverging and opposing chimneys improve SCPP efficiency as the speed value across the chimney increases. A model was run to illustrate the impact of diverging angle for the sun radiation for the Jabalpur site, which is situated 23°10' North latitude and 79°59' East longitude with an average altitude of 411 m from mean sea level **[**2018**]**.

Table 1. Dimensions for Chimney Solar Plant. **(Amin Mohamed El-Ghonemy et al) [2018]**

| **Parameters** | **Value** |
|---|---|
| Chimney height ($H_{ch}$) | 195 m |
| Chimney diameter ($D_{ch}$) | 10 m |
| Collector diameter ($D_{coll}$) | 250 m |
| Distance from ground to the cover ($H_{coll}$) | 2.0 m |
| Efficiency of the Turbine | 0.8 |
| Product of transmittance and absorbance of the collector ($t_a$) | 0.65 |
| Cover heat loss coefficient (ß) | 10 W/m$^2$ |
| Solar irradiance (G) | 800 W/m$^2$ |
| Collector efficiency factor (F’) | 0.8 |

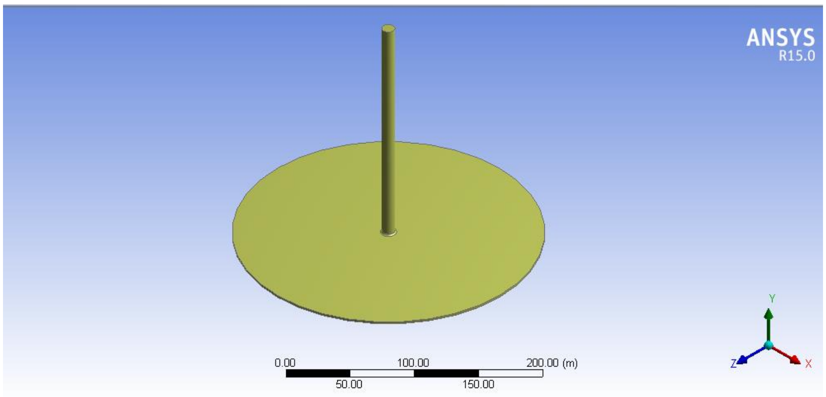



Fig. 1. Geometrical modelling in Ansys CFD.

Table 1 and Figure 1 shows the Dimensions parameters and the geometry developed in Ansys CFD workbench respectively. The meshing or discretization has been carried out and about 32030 nodes and 153501 elements have been generated.

**Thermos Physical Property of the Material**

The Properties of Material have been considered for studies are as:

Table 2. Properties of Material.

| Properties | Air | Glass | Steel |
|---|---|---|---|
| Density (kg/m$^3$) | 1.18 | 2220 | 8030 |
| Specific Heat Cp (J/kgK) | 1006.4 | 830 | 502.48 |
| Thermal Conductivity (W/mK) | 0.0242 | 1.15 | 16.27 |
| Viscosity (kg/mS) | 0.000017894 | | |

**Boundary Conditions**

The boundary conditions have been considered for the studies are as:

Table 3. Boundary Conditions.

| Element | Type | Parameters |
|---|---|---|
| Absorber | Wall and Convection | h = 8 W/m$^2$K |
| Collector Roof | Wall and Convection | h = 8 W/m$^2$K |
| Chimney Surface | Wall and Heat Flux | q = 0 W/m$^2$ |
| Collectoe Inlet | Velocity Inlet | V= 0.5 m/s |
| Collectoe outlet | Pressure Outlet | $P_0$ = 0 Pa |
| Air inlet velocity at collector | | 0.5 m/s |

**Result Analysis**

The solar irradiation was taken constant as the location dependent variable and the divergence angle varied from 1° to 9°. Four variables were considered: Pressure, Temperature, Velocity and Kinetic energy of air. Results were obtained.

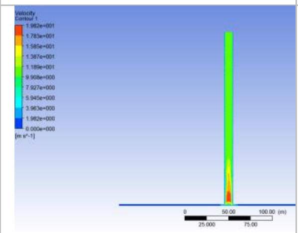
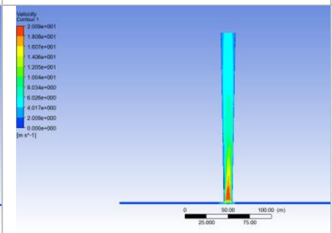
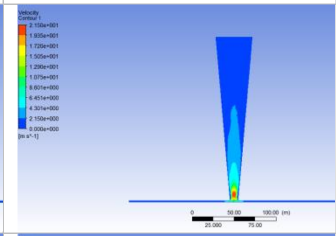
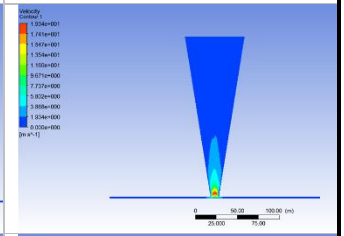
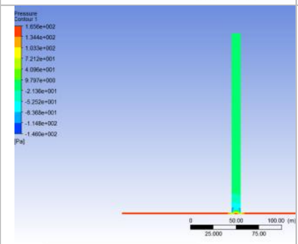
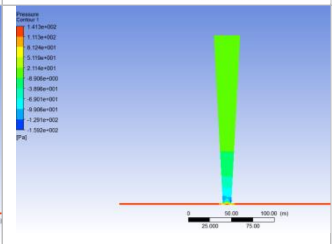
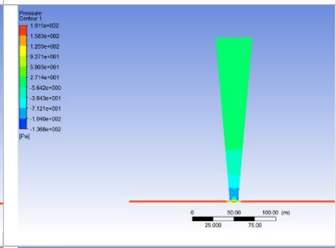
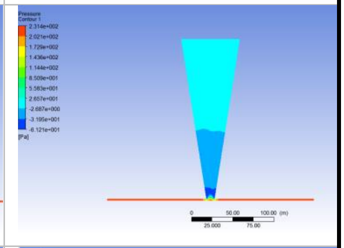
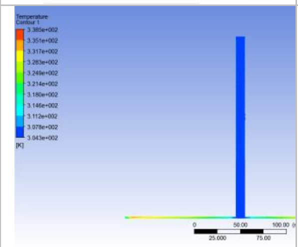
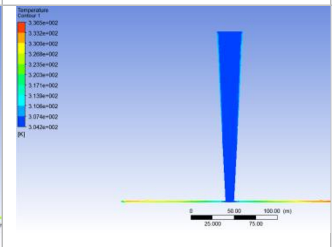
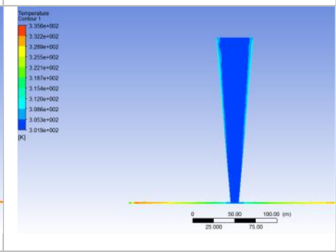
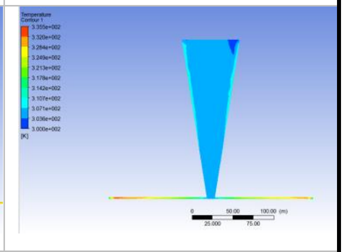
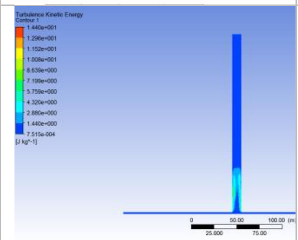
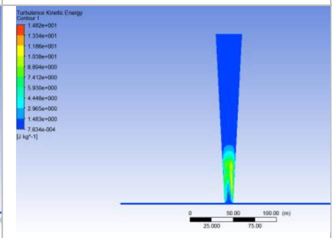
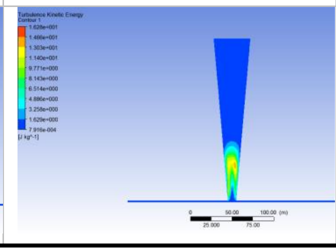
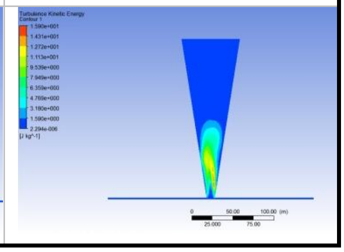
| Variable | 0° | 3° | 6° | 9° |
|---|---|---|---|---|
| Velocity |  |  |  |  |
| Pressure |  |  |  |  |
| Temperature |  |  |  |  |
| Turb. K. E. |  |  |  |  |

Fig. 2. Contours at various operating conditions.

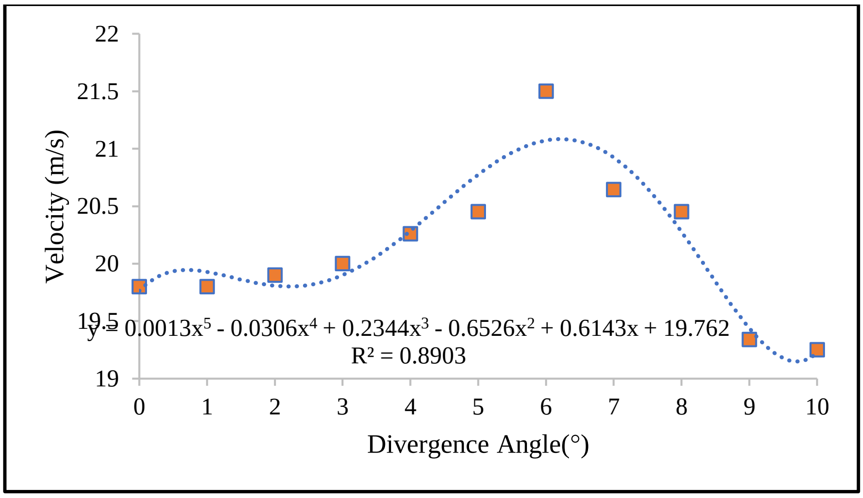



Fig. 3. Variation in air velocity with respect to divergence angle.

Air velocity plays a significant role in the performance of a solar chimney. A solar chimney, also known as a solar updraft tower, is a passive ventilation system that utilizes solar energy to create airflow. The chimney consists of a tall vertical structure with a transparent roof, which allows sunlight to heat the air underneath. The heated air rises and creates an upward airflow, drawing in cooler air from the base of the chimney. Fig 3 illustrates the highest possible air velocity that may be produced within the turbine of a solar chimney power plant for various arrangements, i.e., divergence angle. It is clear from the findings and contours that the chimney design affects how velocity waves are distributed within the structure. The largest velocity rates within the chimney are in the turbine section, and as the chimney cross section rises, they rapidly drop down along the length of the chimney in a direction that is vertical. The maximum air velocity in a typical chimney, which has no divergence, is approximately 19.6 m/s. As divergence is put on, the air velocity declines, but it raises once more as the divergence angle grows. This rise lasts up to 6° of wall inclination, or divergence, following which it starts to drop. Therefore, when it comes to velocity, the highest speed that can be attained is at a 6° angle of divergence chimney turbine.

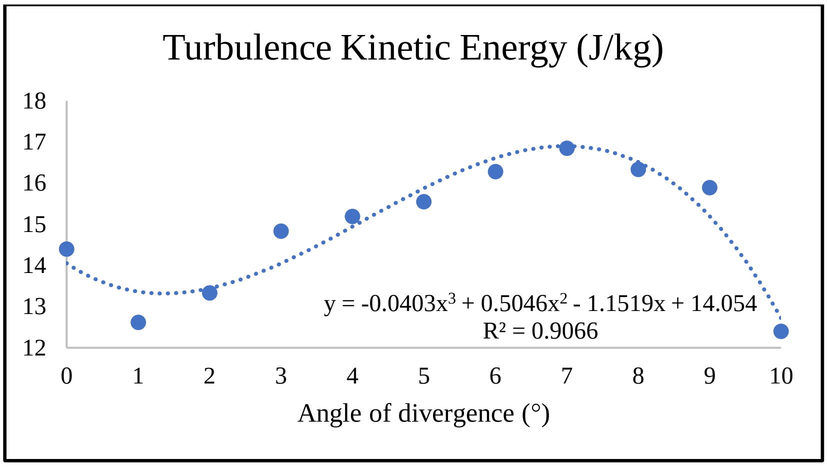



Fig. 4. Variation in turbulence kinetic energy (J/kg) of air with respect to divergence angle.

It is well known that the velocity along the chimney has a direct relationship with the amount energy produced by solar chimney power plants. The highest velocity can be achieved at the neck area in all configurations, and this is the ideal location to attach the turbine to produce the most power, as can be seen from the velocity profile. Based on this knowledge, the divergence angle can be around 6° to provide the greatest power.

Turbulence kinetic energy (TKE) is a measure of the energy associated with turbulent motion within a fluid. In the context of a solar chimney, TKE refers to the energy associated with the turbulent airflow inside the chimney. It is influenced by factors such as the wind speed, geometry of the chimney, and the solar heat input. Turbulence within a solar chimney is generated by the temperature difference between the heated air inside the chimney and the cooler air outside. As the heated air rises, it creates turbulence and mixing, which affects the distribution and intensity of TKE within the chimney. Higher turbulence promotes mixing of the hot air inside the chimney with the cooler ambient air. This mixing is beneficial for heat transfer, as it helps distribute the thermal energy more evenly throughout the airflow. It can lead to improved efficiency in heat exchange processes and more effective power generation. Higher TKE levels can lead to increased pressure drop within the chimney. This is due to the increased friction and resistance caused by the turbulent flow. A higher-pressure drop can impact the overall performance of the system, as it requires additional energy to overcome the resistance and maintain the desired airflow rate.

The turbulent kinetic energy (J/kg) of Air with respect to Divergence Angle. The turbulent kinetic energy shows the same behaviour as the velocity profile shows. At divergence angle between 6-7° the turbulent kinetic energy is maximum and after that it decreases.

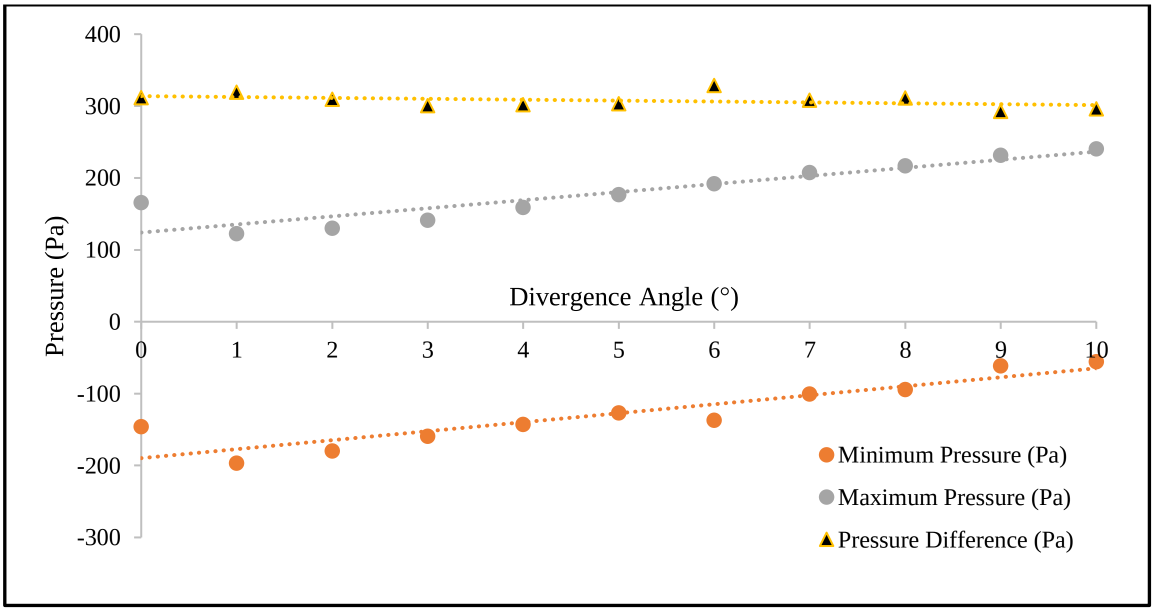


Fig 5 Variation in Pressure of Air with respect to Divergence Angle

In the context of a solar chimney, pressure drop is an important consideration as it affects the airflow rate and the overall performance of the system. Fig 5 shows the maximum pressure of Air with respect to divergence Angle. From the contours in the last section, it is observed that the pressure difference (i.e., the difference between maximum and minimum pressure) increases as the divergence angle increases up to 6° and decreases again.

The highest pressure increased as the divergence angle increased, and the law of ideal gases forced the temperature to fall. Heat buoyancy, and which results from a change in air's density with a degree in temperature across the input and outflow, is the primary force behind air movement inside chimney cavities. The heat held in the earth raises the temperature of the air inside the chimney, which improves the draught. For various values of divergence angle, the figure in the preceding sections displays temperature gradients within the solar chimney at the collector's and chimney input and exit. The highest temperature has been seen to rapidly fall as the divergence angle rises starting at 1°. this is because when air velocity rises, heat transfer rates rise and the peak temperature falls.

## Conclusion

In the present study, a numerical simulation of the solar chimney performance considering the different divergence angle has been carried out. The effects of the divergence angle on pressure drop, temperature, turbulent kinetic energy, and velocity inside the chimney plant of air has been examined. The following conclusions obtained:

- The distribution of velocity fields inside the system varies with the chimney configuration, and the maximum velocity that can be achieved is at 6° angle of divergence chimney turbine.
- The maximum velocity is obtained at the neck area in all configurations and is the optimum place to install the turbine to get maximum power.
- The turbulent kinetic energy shows the same behavior as the velocity profile, and the pressure difference increases as the divergence angle increases up to 6° and decreases again.
- Increasing the divergence angle caused maximum pressure to increase and, due to the ideal gas law, the temperature decreased.
- It has been observed that from 1° divergence angle the maximum temperature decreases rapidly as the divergence angle increases.

While considering the above four factors the divergence angle 6° is more optimized while varying the divergence angle from 0-10°.

### *Abbreviations*

$H_{ch}$: Chimney height
$D_{ch}$: Chimney diameter
$D_{col}$: Collector diameter
$H_{coll}$: Distance from ground to the cover
Ɵ: Divergence angle
Ta: Product of transmittance and absorbance of the collector
ß: Cover heat loss coefficient
G: Solar irradiance
F: Collector efficiency factor

## References


1) Abdallah Bouabidi, Ahmed Ayadi, Haytham Nasraoui, ZiedDriss, Mohamed Salah Abid, Study of solar chimney in Tunisia: Effect of the chimney configurations on the local flow characteristics, Energy & Buildings (2018), doi: 10.1016/j.enbuild.2018.01.049.
2) Ahmed Abdeen, Ahmed A. Serageldin, Mona G.E. Ibrahim, Abbas El-Zafarany, Shinichi Ookawara, Ryo Murata ; Solar chimney optimization for enhancing thermal comfort in Egypt: An experimental and numerical study, Solar Energy 180 (2019) 524–536.
3) Amin Mohamed El-Ghonemy, Solar Chimney Power Plant with Collector, IOSR Journal of Electronics and Communication Engineering (IOSR-JECE),2018.
4) B. Belfuguais, S. Larbi, Passive Ventilation System Analysis using Solar Chimney in South of Algeria, World Academy of Science, Engineering and Technology International Journal of Mechanical and Mechatronics Engineering Vol:5, No:10, 2011.

5) Cao F, Liu Q, Yang T, Zhu T, Bai J, Zhao L, Full-year simulation of solar chimney power plants in Northwest China, Renewable Energy(2018), doi: 10.1016/j.renene.2017.12.022.
6) Hardi A. Muhammed, Soorkeu A. Atrooshi; Modeling solar chimney for geometry optimization, Renewable Energy 138 (2019) 212-223.
7) Hussain H. Al-Kayiem, Mohammed A. Aurybi, Syed I.U. Gilani, Ali A. Ismaeel, Sanan T. Mohammad, Performance Evaluation of Hybrid Solar Chimney for Uninterrupted Power Generation, Energy (2018), doi: 10.1016/j.energy.2018.10.115.
8) P.J. Cottam, P. Duffour, P. Lindstrand, P. Fromme, Solar chimney power plants – Dimension matching for optimum performance, Energy Conversion and Management 194 (2019) 112–123.
9) Seyyed Hossein Fallah, Mohammad Sadegh Valipour, Evaluation of solar chimney power plant performance: The effect of artificial roughness of collector, Solar Energy 188 (2019) 175–184.
10) Shi, Guomin Zhang, Wei Yang, Dongmei Huang, Xudong Cheng, SujeevaSetunge, Determining the influencing factors on the performance of solar chimney in buildings Long, Renewable and Sustainable Energy Reviews 88 (2018) 223–238.
11) Omar A. Najm, S. Shaaban; Numerical investigation and optimization of the solar chimney collector performance and power density, Energy Conversion and Management 168 (2018) 150–161.
12) Omer Khalid, Ahmed and Abdullah Sabah Hussein, New design of Solar Chimney (Case study), Case Studies in Thermal Engineering(2018)
13) P. Parthasarathy, N.A. Pambudi, Performance study of a solar chimney air heater, Case Studies in Thermal Engineering (2019), doi: https://doi.org/10.1016/j.csite.2019.100437.
14) Saeed Dehghani, Amir H. Mohammadi; Optimum dimension of geometric parameters of solar chimney power plants – A multi-objective optimization approach, Solar Energy 105 (2014) 603–612.
15) SuhilKiwan, Moh'd Al-Nimr, Qamar I. Abdel Salam, Solar chimney power-water distillation plant (SCPWDP), Desalination 445 (2018) 105–114.
16) Toghraie D, Karami A, Afrand M, Karimipour A, Effects of geometric parameters on the performance of solar chimney power plants, Energy (2018), doi: 10.1016/j.energy.2018.08.086.
17) Vargas-López R, Xamán J, Hernández-Pérez I, Arce J, Zavala-Guillén I, Jiménez MJ, Heras MR, Mathematical models of solar chimneys with a phase change material for ventilation of buildings: A review using global energy balance, Energy (2019).
18) Fluri TP, Pretorius JP, Dyk CV, von Backström TW, Kröger DG, van Zijl GPAG. Cost analysis of solar chimney power plants. Solar Energy 2009; 83:246–56.
19) Bernardes MA dos S. Technische, ökonomische und ökologische Analyse von Aufwind-kraftwerken PhD Thesis Universität Stuttgart; 2004 Schlaich J, Bergermann R, Schiel W, Weinrebe G. Sustainable electricity generation with solar updraft towers. Struct Eng Int 2004;14: pp. 225–9.
20) Li W, Wei P, Zhou X. A cost-benefit analysis of power generation from commercial reinforced concrete solar chimney power plant. Energy Convers Manage 2014;79: pp. 104–13.
21) Guo P, Zhai Y, Xu X, Li J. Assessment of levelized cost of electricity for a 10-MW solar chimney power plant in Yinchuan China. Energy Convers Manage 2017; 152:176–85.
22) Shirvan KM, Mirzakhanlari S, Mamourian M, Abu-Hamdeh N. Numerical investigation, and sensitivity analysis of effective parameters to obtain potential maximum power output: a case study on Zanjan prototype solar chimney power plant. Energy Convers Manage 2017; 136:350–60.
23) Gholamalizadeh E, Kim M-H. Thermo-economic triple-objective optimization of a solar chimney power plant using genetic algorithms. Energy 2014;70: 204–11.
24) Okoye CO, Solyalı O, Taylan O. A new economic feasibility approach for solar chimney power plant design. Energy Convers Manage 2016;126: 1013–27.
25) Nizetic S, Ninic N, Klarin B. Analysis and feasibility of implementing solar chimney power plants in the Mediterranean region. Energy 2008;33: 1680–90.
26) Ali B. Techno-economic optimization for the design of solar chimney power plants. Energy Convers Manage 2017;138: 461–73.
27) Zhou X, Yang J, Xiao B, Hou G, Xing F. Analysis of chimney height for solar chimney power plant. ApplTherm Eng 2009;29: 178–85.
28) Dehghani S, Mohammadi AH. “Optimum dimension of geometric parameters of solar chimney power plants – a multi-objective optimization approach. Sol Energy 2014;105:603–12.
29) Pretorius JP, Kröger DG. Thermoeconomic optimization of a solar chimney power plant. J Sol Energy Eng 2008.