Theoretical and Experimental Investigation of Solar Updraft Tower Power Plant: A Case Study in El-Beida City

Alhassan Mohammed[1], Tarek Hamad[2], Mohammed Fawzi[3], and Fouzi Mossa[4]

***Abstract*—As the population grows, the demand for energy and the consumption of fuel increases as well. Causing carbon dioxide emissions to rise at an alarming rate affecting the ecosystem heavily. Moreover, the quantity of fossil fuel is depleting leading to search for a more sustainable energy source. This study presents the design of an experimental small pilot to collect data about temperature distribution and air velocity also to predict the power that can be produced, the solar radiation intensity, environment temperature, and the ambient air velocity is collected to, a mathematical model of the system has been worked out to evaluate its data with the experimental data.**

***Key Words*— Solar radiation, solar updraft tower, El-Beida City, experimental and mathematical modeling.**

I. INTRODUCTION

WHILE today's societies are starting to acknowledge renewable energy potentials as an alternative energy source due to being environmentally friendly and therefore the undeniable fact that during this field harness the facility of a non-depleting power supply, therefore, the name renewable is in fact not a recent trend during which humans discover the way to harness energy from nature for thousands of years. however once oil and fossil fuels were first discovered within the decade With great potential at the time, with the passage of time, major industrial societies began to understand that fossil fuels were already depleted at an alarming rate due to excessive use and increasing demand. It's environmental negatives witnessed for the first time The change in the reliability of mankind to clean energy sources, that are the results of natural and repetitive movement in the surrounding isn't a new technological concept, and any energy that occurs naturally and inexhaustible, like wind, biomass, solar, tides, wave and hydropower that don't derive from fossil fuels within the name of renewable energy. The importance of this rising field is even more apparent after we have to be compelled to find ways in which to provide clean, safe and economical energy devices while not damaging the atmosphere. The solar updraft towers are power plants that produce electricity by straightforward however economical operation by using the solar power to form density difference between the air layers within the collector and therefore the air in the chimney, that acts because of the same principle as the greenhouse. it's a solar thermal station composed of an air collector (greenhouse), a tower (chimney) to get the variation in pressure in order that the warmth load flows from the solar power and a rotary engine unit moves through the heat transfer fluid (HTF). This fluid is found below the greenhouse to provide electricity. Feasible technology-centered to utilize renewable energy should be uncomplicated and reliable, approachable to the developed communities that are sunny and infrequently have limited raw resources, and therefore the technology required to operate. It should not need a cooling agent and should be based on eco-friendly and recyclable materials. Thus the solar updraft tower meets these needs. A typical illustration of the concept and technology behind the solar updraft tower is shown in Fig.1.

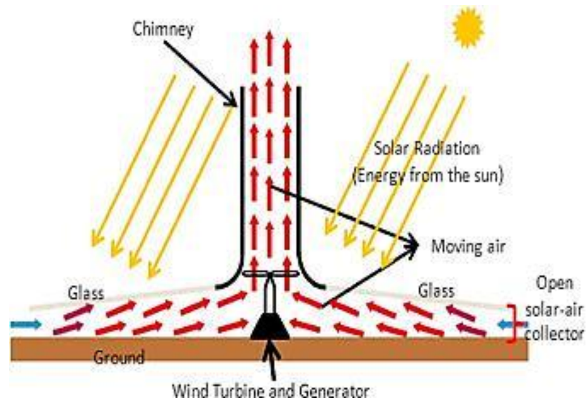

Fig.1. Solar chimney system (Al-Kayiem and Aja, 2016)

The use of radiation to heat the air and later convert it into a supply of energy was planned in 1903[1], once the Spanish army commissioned military officer, Isidoro Cabanyes, submitted a proposal for a solar chimney to la Energia Electrica[2]. additionally, Hanns Gunther experimented to prove its effectiveness in Manzanares, Spain within the 1980s [3]. The collector was concerning 244m diameter whereas the chimney was about 200m tall and 5.08m diameter [4]. The plant produces energy of concerning 50 kW [5].

[1]Department of Mechanical Engineering, Omar Almukhtar University, Derna, Libya.
[2]Department of Sustainable and Renewable energy, Omar Almukhtar University, Elbieda, Libya.
[3]Department of Sustainable and Renewable energy, Omar Almukhtar University, Derna, Libya.
[4]Department of Mechanical Engineering, Omar Almukhtar University, Elbieda, Libya.
alhassan.mohammed@omu.edu.ly[1]
tah5xd@mst.edu[2]
mohammed.fawzi@omu.edu.ly[3]
fauzi.mossa@omu.edu.ly[4]

Since then a lot of researchers shows a good concern in it to check the potential of the solar updraft towers around the world. Pasumarthi and Sherif [6] engineered a demonstrated model of a solar chimney power station in Florida, America, and they place two enhancements to the system by extending the collector and put an absorbent medium to increase the facility efficiency. In [7] analyzed the solar chimney power station as an ideal air cycle, the anlysis includes chimney friction turbine and mechanical energy losses and created a mathematical model to predict the performance of an large scale plant, the model additionally variated by comparison it with an information of a small scale. Another study [8] described his sensible expertise and economy on the solar updraft tower, and therefore the knowledge of building and operating the solar updraft power station in the European nation was presented and mentioned to apply the same system in Australia. In Aswan, Egypt [9] a solar chimney was constructed the chimney height was 20.0 m, its diameter was 1.0m, and therefore the collector was a four-sided pyramid, that had a length of 28.5 m. A mathematical model is employed to predict its performance. The model shows that the plant will turn out the most theoretical power of 2 kW. Abuashe [10] implemented an experimental small scale pilot within the town of Subrata west Libya the collector surface is in a circular form with area of 126m^2 the solar chimney was a PVC tube with internal diameter of 0.2 m, and therefore the total height of chimney was 9.8 m then collected data are evaluated with a mathematical model to predict the performance of the pilot. Solar updraft towers also called solar wind or solar flue plants, provide a simple technology to generate renewable electricity, with steady and reliable production. different renewable sources of energy, like wind turbines and solar arrays, suffer from the big day and seasonal fluctuations or sudden production patterns. One of the numerous perks that The solar updraft tower technology has over the traditional solar energy plant technology lays in its simple flexible design, and therefore the fact that this station employs lesser moving elements than different solar energy harnessing strategies ensuing reduction in maintenance expenses in the long term, a comprehensive researches covering a large and thorough experiments on structure ,indicates that the thermodynamical analysis for the parts of the solar updraft tower (**SUT**) well performance and responsibility for all sizes in broad region across planet [8].

The study of solar updraft power stations in Libya has not been sufficiently addressed. Moreover, this paper provides an outline of this technology, together with each a mathematical model and experimental information measuring. Ultimately, this study will provide an experimental small pilot model to gather data regarding temperature and air distribution to predict the output that can be produced as a case study in El-Beida city, Libya.

II. METHODOLOGY

The methodology of this paper is to construct a small scale pilot of solar updraft tower by recycled materials:

- A black Pvc pipe with a diameter of 0.11m and 2.5m tall as a chimney.
- A plastic cover (the collector) with a diameter of 2m.
- A metal base structure as a holder to the collector and also the chimney.
- A small PC fan as a turbine.

The pilot helped to collect data about:

- The solar intensity.
- Heat distribution in the collector.
- Air velocity in the collector.
- The ambient air temperature.

The speed of ambient air.

III. MATHEMATICAL MODEL

The mathematical model depends on the basic governing equations of fluid dynamics – the continuity, momentum, and energy equations. they're the mathematical statements of three fundamental physical principles upon that each one of fluid dynamics is based:

1) Mass is conserved, 2) Newton's second law, 3) Energy is conserved

These three fundamental principles are written in the style of partial differential equation as shown below

Continuity equation:

$$\frac{\partial}{\partial t}\rho + \left(\nabla \cdot \rho\vec{V}\right) = 0 \qquad (1)$$

Momentum equation:

$$\frac{\partial}{\partial t}\rho\vec{V} + \rho\vec{V}\cdot\left(\nabla\vec{V}\right) = -\nabla p + \rho\vec{\mathcal{F}}_{body} + \vec{\mathcal{F}}_{viscous} \qquad (2)$$

Energy equation:

$$\frac{\partial}{\partial t}\left[\rho\left(e+\frac{\vec{V}^2}{2}\right)\right] + \nabla\cdot\left[\rho\left(e+\frac{\vec{V}^2}{2}\right)\vec{V}\right] = \rho\dot{q}_{addition} + \dot{q}_{viscous} - \nabla\cdot\left(p\vec{V}\right) + \rho\left(\vec{\mathcal{F}}_{body}\cdot\vec{V}\right) + \dot{w}_{viscous} + \dot{w}_{external} \qquad (3)$$

The State equation is:

$$p = \rho RT \qquad (4)$$

The assumptions are taken into consideration:

1. (Steady state) incompressible flow.
2. The flowing air in the system is considered as an ideal gas.
3. The heat transfer through the collector is uniform because it is thickness is very small.
4. The heat transfer is in one-dimension in the (y-direction)./one-dimensional heat transfer in the (y-direction).
5. The fluid moves in the axis of (r -direction).
6. The collector is a transparent roof admits direct and diffused solar radiation and retains long-wave radiation from the ground (absorber).
7. The heat losses from collector edges are negligible.
8. The air is flowing in the radial direction.
9. The heat losses through the wall of the chimney are neglected [9].
10. The type of convection heat transfer in the collector is regarded as natural convection.

As shown Fig.2 all the sections of the solar updraft tower have been numbered, therefore the rise in temperature according to this station can be calculated from the energy equation:

$$m^{\cdot} * C_P * (T_2 - T_1) + m^{\cdot} * \frac{(V_2^2 - V_1^2)}{2} = Q * A_{coll} \quad (5)$$

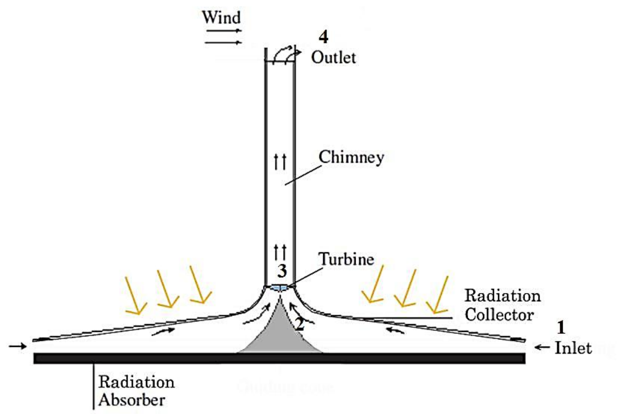

Fig.2. Schematic layout of a solar chimney power plant(Wang et al., 2012)

Because of the small impact of friction and the low of Mach number the kinetic energy can be neglected so that,

$$m^{\cdot} * C_P * (T_2 - T_1) = Q * A_{coll} \quad (6)$$

By using the energy equation and Gibbs equation the analytical power that can be extracted from the turbine can be determined from:

$$W^{\cdot}_{analytical} = m^{\cdot} \int \nu * dp = \frac{m^{\cdot}}{\frac{\rho_3+\rho_2}{2}} * (P_2 - P_3) \quad (7)$$

Where:

$$m^{\cdot} = \rho_{turb} * A_{chim} * V \quad (8)$$

$$A_{chim} = \frac{\pi}{4} * d_{chim}^2 \quad (9)$$

$$\rho_{turb} = \frac{\rho_2+\rho_3}{2} \quad (10)$$

By using [11] developed model, momentum, and energy of the flow under the collector:

$$P_2 = P_1 + m^{\cdot} * \frac{I}{2*\pi*h_{coll}^2*\rho_1*C_P*T_1} \ln\left(\frac{r_{coll}}{r_{chim}}\right) - \frac{m^{\cdot 2}}{2*\rho_1} * \left(\frac{1}{A_2^2} - \frac{1}{A_1^2}\right) \quad (11)$$

According to [12]:

$$Q = I * \alpha - U * (T_2 - T_1) \quad (12)$$

And from equation (6):

$$Q = \frac{m^{\cdot} * C_P * (T_2 - T_1)}{A_{coll}} \quad (13)$$

By manipulating:

$$(T_2 - T_1) = \frac{I * \alpha}{\frac{(m^{\cdot} * C_P)}{A_{coll}} + U} \quad (14)$$

According to [13] U=5w/m^2 and α=0.76. The process from 2 to 3 is considered as an isentropic process:

$$T_3 = T_2 * \left(\frac{P_3}{P_2}\right)^{\frac{\gamma-1}{\gamma}} \quad (15)$$

By manipulating the momentum and continuity equation for the cross-section area of the chimney the pressure P_3 will be:

$$P_3 = P_4 + \left(\frac{\rho_3+\rho_4}{2}\right) * g * h_{chim} + \left(\frac{m^{\cdot}}{A_{chim}}\right)^2 * \left(\frac{1}{\rho_4} - \frac{1}{\rho_3}\right) \quad (16)$$

The chimney has a negative impact on pressure due to negative work done by gravitational force:

$$dP = -\rho * g * dz \quad (17)$$

Hence the heat is decreasing bcause of this impact therfore:

$$T = T_{amb} - \frac{g}{C_p} * h_{chim} \quad (18)$$

The air is assumed as an ideal gas and by replacing equation (18) in equation (17), P_4 can be calculated by:

$$P_4 = P_{amb} * \left(1 - \frac{g}{C_p * T_{amb}} * h_{chim}\right)^{\frac{C_p}{R}} \quad (19)$$

From equation (18) and by similarity:

$$T_4 = T_3 - \frac{g}{C_p} * h_{chim} \quad (20)$$

By using the equation of state:

$$\rho = \frac{p_2}{RT_2} \qquad \rho = \frac{p_3}{RT_3} \qquad \rho = \frac{p_4}{RT_4} \quad (21)$$

According to [14], the theoretical driving pressure ΔP_{tot} the difference between the pressure of cold air at point (1), and the

Pressure of hot air at point (3):

$$\Delta P_{tot} = p_1 - p_3 \quad (22)$$

The solution procedure is shown in Fig.3:

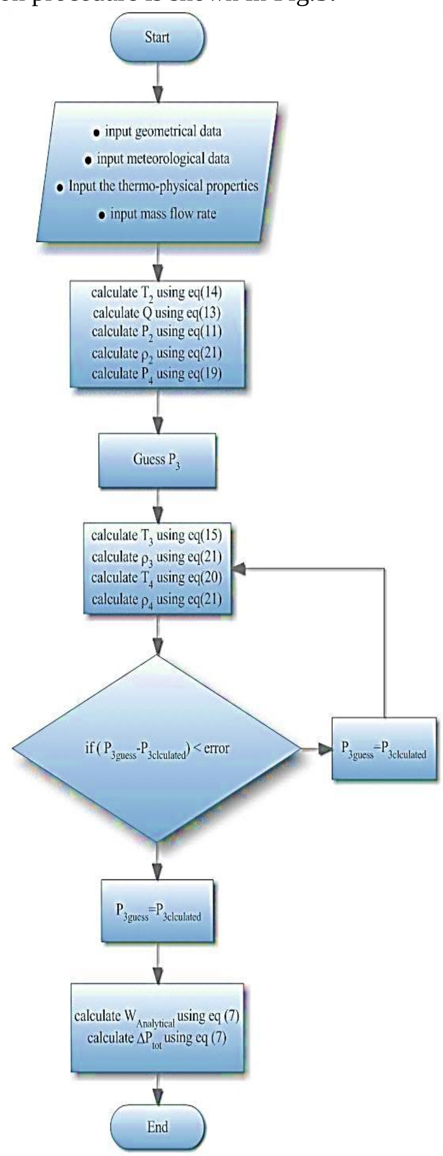

Fig.3. Flow chart of the solution method

IV. Experimental Procedure

A. The building of a pilot setup:

To perform a detail investigation into the measured temperature field in solar chimney power system, a pilot experimental setup as shown in **Fig.4** consisted of an air collector 2 m in diameter and a 2m tall chimney was built, and to avoid the shadows of buildings on the collector, the solar chimney power setup was built on the roof of a building in El-Beida, Libya.

Fig.4. Picture of the experimental solar chimney power setup

The framework of the collector 2 m in diameter was constructed of Steel iron base with dimensions of (60X100 cm) to ensure enough strength to resist strong winds because the experimental setup was located outdoors. In order to produce a greenhouse effect, a single plastic tube sheet of transparent plastic was used to cover the framework. The function of the plastic tube filled with water and closed on the ground under the collector is absorption and storage of solar energy

B. Measuring the temperature and velocity distribution:

An infrared thermometer was used to measure air temperatures. We chose 6 typical points in the collector as shown in **Fig.5**. The points of 1–6, in the collector, were used to measure air temperatures and velocity. Further, a thermal anemometer with the accuracy of ±0.5°C ±0.01 m/s is used to measure the velocity of airflow and to measure the ambient temperature and ambient air velocity.

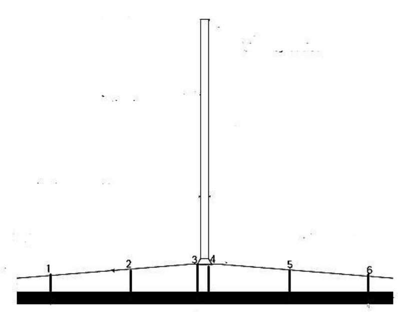

Fig.5. The distribution of test points

V. Results and Discussion

A. Experimental results:

In the course of experimental measuring, the turbine generator is under no-load conditions. Taking the experimental results obtained in the solar updraft set up on July for 3rd, 4th , 5th 2019 at 6:00 am to 8:00 pm for each hour as an example, the solar radiation on the setup is shown **Fig.6**, the distribution of air temperatures at different points under the collector in the setup are shown in **Fig.7**. In **Fig.6** the solar radiation information gathered for three days indicates that the 3rd of July day had the greatest solar radiation gain approximately 1000W / m^2, therefore the data of 3rd day is taken into consideration and discussed.

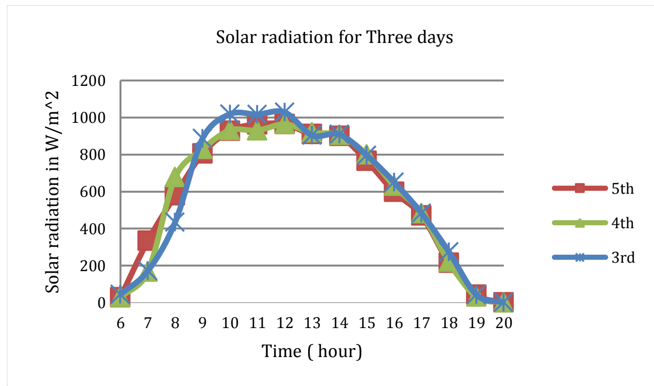

Fig.6. Solar radiation for three days

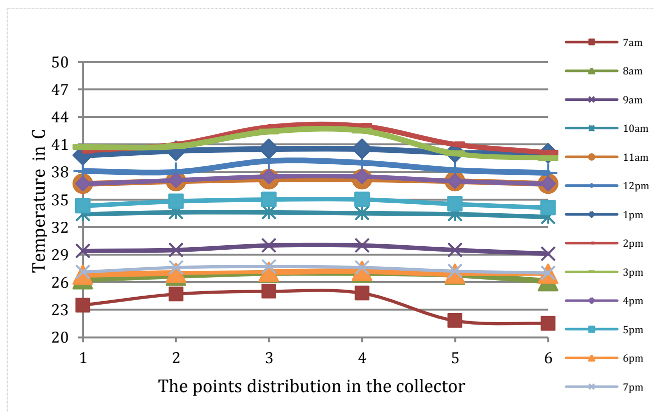

Fig.7. Heat distribution under the collector

Fig.7 presents the variations of air temperatures within the collector, and some conclusions can be drawn as follows:

1) The variations of air temperatures in the two sides of the collector are nearly uniform. However, the air temperatures at points of 1–3 in the collector are a little greater than those at points of 4–6, because the southern side is more exposed to sunlight and the setup is located in the Northern Hemisphere where the southward sloping surface of the collector will let solar radiation in with higher efficiency than northward sloping surface of the collector.

2) The temperatures usually increase from the periphery to the center. The temperatures at the point of 3-4 are usually the highest, since that the point of 3-4 is located near the center of the collector. the results at the point of 6 are the

lowest because point 6 is located in the north and close to the collector opening.

Taking the experimental results obtained on July 3rd, 2019 as an example, data of air velocity in the chimney inlet and ambient airspeed at different times of day from 6:00 am to 8:00 pm were measured, and are shown in Fig.8.

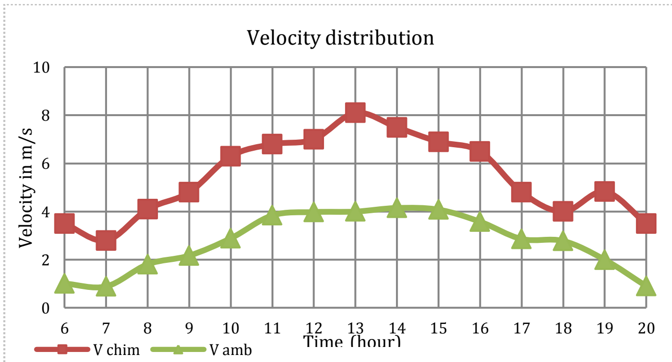

Fig.8. Air velocity of chimney inlet and ambient air velocity

As seen from **Fig.8**, the distributions of chimney air velocity are not uniform as a result of the fluctuation of hot air accumulated under the chimney, the difference between chimney air velocity and ambient airspeed is reached the peak value at 1:00 pm and it was about 4m/s.

B. Mathematical model results

To validate the analytical model, the theoretical data were compared with the experimental results of the small scale prototype from El-Beida, Libya. The comparisons between the theoretical predictions and the experimental values are presented in (Fig.9 and Fig.10)

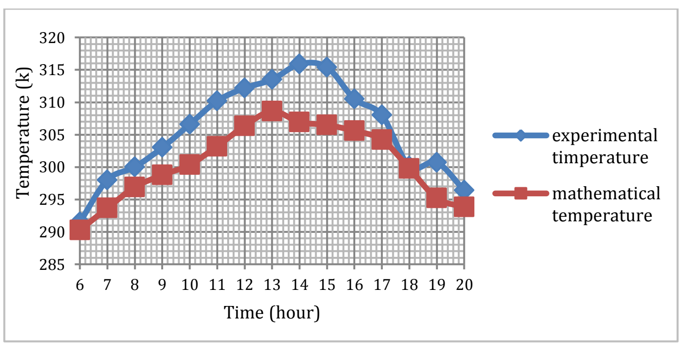

Fig.9. Comparison between the experimental and mathematical model in the chimney inlet temperature value

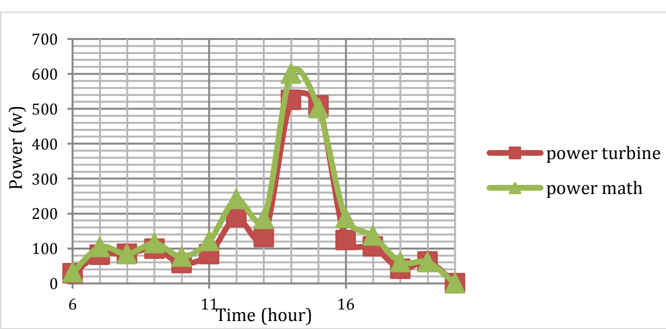

Fig.10. Comparison of experimental and mathematical model in the power output

The theoretical results display the same general trend of the experimental. It is noted from (Fig.9 and Fig.10) There is an agreement between the experimental results and that predicted by the present model. However, some differences between the measured and predicted results do exist due to the assumptions and idealizations of the analysis.

VI. Conclusion

In this study, a small-scale experimental model was constructed and used to conduct measurements to study solar chimney system performance, as well as a mathematical model to predict the solar updraft tower's energy output. In El-Bieda City, Libya, a pilot experimental setup was constructed to explore the temperature distribution as well as examine the impact of day time on the temperature field. A 2m diameter collector was constructed on a base of a steel frame. A 2 m high chimney was made of 0.11m diameter PVC drainpipes. In this paper, researchers evaluated the temperature distribution in the solar updraft tower based on the experimental temperatures measured in the solar updraft tower. The temperature difference between the collector outlet and the environment can usually reach 10°C, responsible for generating the airflow driving force in the system. This is the greenhouse effect that the solar collector produces. The results of the present theoretical model have been compared with the results of the small-scale prototype experimental work. The results were at a good agreement.

References

[1]. Cao, F., Zhao, L., and Guo, L. (2011). Simulation of a sloped solar chimney power plant in Lanzhou, Energy conversion and management, 52, (6), pp. 2360-2366

[2]. Miñana, J.S. (2014). El Artillero Isidoro Cabanyes (1843-1915): Una Vida de Inventos, Quaderns d'Història de l'Enginyeria, 2014, 14, pp. 83-154

[3]. Schlaich, J. 1995. The solar chimney: electricity from the sun, (Edition Axel Menges, 1995)

[4]. Haaf, W., Friedrich, K., Mayr, G., and Schlaich, J. (2007). Solar Chimneys Part I: Principle and Construction of the Pilot Plant in Manzanares', International Journal of Solar Energy, 2, (1), pp. 3-20

[5]. Haaf, W.(1984). 'Solar chimneys: part ii: preliminary test results from the Manzanares pilot plant', International Journal of Sustainable Energy, 2, (2), pp. 141-161

[6]. Pasumarthi, N., and Sherif, S. (1997). 'Performance of a demonstration solar chimney model for power generation', CALIFORNIA STATE UNIV, SACRAMENTO, CA,(USA), pp. 203-240

[7]. Gannon, A.J., and von Backström, T.W. (2000). Solar Chimney Cycle Analysis With System Loss and Solar Collector Performance', Journal of Solar Energy Engineering, 122, (3), pp. 133

[8]. Schlaich, J., Bergermann, R., Schiel, W., and Weinrebe, G. (2005). Design of commercial solar updraft tower systems—utilization of solar induced convective flows for power generation, Journal of Solar Energy Engineering, 127, (1), pp. 117-124

[9]. Harte, R., Tschersich, M., Höffer, R., and Mekhail, T. (2017). Design and Construction of a Prototype Solar Updraft Chimney in Aswan/Egypt, Acta Polytechnica, 57, (3)

[10]. Abuashe, I.A.T.(2018). Experimental and theoritical investigation of performance of a solar chimeny model, part 2: theoritical investigation.

[11]. Chitsomboon, T. (2001). A validated analytical model for flow in solar chimney', International Journal of Renewable Energy Engineering, 2001, 3, (2), pp. 339-346

[12]. Duffie, J.A., and Beckman, W.A.(2013). 'Solar engineering of thermal processes' (John Wiley & Sons, 2013)

[13]. Koonsrisuk, A., and Chitsomboon, T. (2013). Mathematical modeling of solar chimney power plants, Energy, 51, pp. 314-322
[14]. Zhou XP, B.M.d.S., Ochieng RM. (2012). Influence of atmospheric cross flow on solar updraft tower inflow', Energy, 42(1), pp. 393-400

NOMENCLATURE

A	flow area, m^2
A_{coll}	collector area, m^2
cp	specific heat capacity at constant pressure, J/(kg K)
g	gravitational acceleration, m/s^2
h_{chim}	chimney height, m
h_{coll}	roof height above the ground, m
I	solar irradiation, W/m^2
m	mass flow rate, kg/s
p	pressure, Pa
Q	insolation, W/m^2
R	ideal gas constant, J/kg K
r_{chim}	chimney radius, m
r_{coll}	roof radius, m
T	absolute temperature, K
U	collector loss coefficient, W/m^2 K
V	flow velocity, m/s
$W_{analytical}$	power, W
Greek symbols	
α	collector absorption coefficient
ΔP_{tot}	pressure drop, Pa
γ	specific heat ratio
ρ	density, kg/m^3
Subscripts	
1,2,3,4	position along solar updraft
chim	chimney
tot	total pressure component
PVC	polyvinyl chloride