A Review on Solar Chimney Systems

A.B. Kasaeian[1]*, Sh. Molana[2], K. Rahmani[3], D. Wen[4]

[1,2,3]Department of Renewable Energies, Faculty of New Science and Technologies, University of Tehran, Tehran, Iran.

[4]School of Chemical and Process Engineering, University of Leeds, Leeds, United Kingdom.

Corresponding author: akasa@ut.ac.ir, Tel: +98-9121947510, Fax: +98 21 88617087

Abstract

The increased utilization of solar energy has gained the attention of researchers to develop the solar chimney (SC) technology in recent years. Many studies have been conducted in this aear both experimentally and theoretically, whereas experimental studies are mainly focused on small-scale systems. This work provides a comprehensive and updated review that include most of the experimental studies, analytical and simulation works, the solar chimney applications, hybrid systems and geographical case studies based on extended references, citation of the updated works and the specified way of looking at different sections. The technological gaps in differnet sections are identified and a summary of suggestions is given for the future work, including more experimental works on the large-scale systems, and CFD analyses for optimization between the geometrical parameters and the output power. More studies on new applications of solar chimney technology including hybrid systems are also recommended.

Keywords: Solar chimney; collector; turbine; power conversion unit; solar updraft tower.

Contents

1. Introduction

A solar chimney system consists of a solar collector, a chimney and a turbine (Fig. 1), which is also named as Solar Aero-Electric Power Plant (SAEP). It uses solar insolation to increase the temperature of the air, and the buoyancy force causes the flow of the air stream inside the solar chimney system. Air is warmed up due to the greenhouse effect under a transparent collector.

Cabanyes [1] proposed the solar chimney power technology for the first time. In this system, a chimney was utilized for air heating of a house. Inside the house, a type of wind blade was located for the purpose of electricity generation. Several patents were registered in Australia, the USA, and Canada since 1975 [2]. The first solar chimney power plant (SCPP) prototype was designed and constructed by Schlaich [3], [4] and his colleagues in Manzanares, Spain, between 1981 and 1982, After establishing this plant, many researchers in different countries proposed their solar chimney designs and buildings. A large project with 200 MW was assigned by the government of Australia in Mildura. The proposed solar chimney in Australia was supposed to be 1000 m in height and 7000 m in the collector diameter. The output power of this plant was supposed to be capable of supplying power for 200,000 households [5], [6]. A program for constructing a 100 MW SCPP in a desert in Rajasthan, India, was also scheduled, but was aborted later on due to the political tension between India and Pakistan [7]. A proposal of building of a 40 MW SCPP , called the Ciudad Real Torre Solar with a 750 m high chimney and 3.5 km^2 collectors in Ciudad Real, Spain, was presented [8]. The Namibian government agreed in 2008 to build a 400 MW SCPP, called the "Green Tower" with a solar chimney 1500 m high, 280 m chimney diameter, and 37 km^2 collector, which was also proposed to act as a greenhouse for agriculture applications [9]. Building of a 1000 m high solar chimney was suggested in Shanghai, China for tourism plans and power generation, and its validation was performed by the HUST team [10].

The review by Zhou et al. [10] provided a general vision of research and development of solar chimney power technology up to 2010. After the introduction of the basic physical process of solar chimney, they reviewed the experimental and theoretical studies, and discussed the economic aspects of solar chimney and some different types of solar chimneys such as floating solar chimney, solar chimney with sloped collector and mountain-laid chimneys. Chikere et al. [11] reviewed the previous studies focusing on the enhancement techniques of SCPP until 2011.

An alternative enhancement technique, which utilizes waste thermal energy in the flue gas as the energy input in a solar chimney collector, was also proposed. Zhai et al. [12] provided a review of solar chimney applications in buildings in 2011, and summarized the applications of solar chimneys based on roof and walls of buildings and also the integrated configurations based on solar chimneys. Dhahri and Omeri [13] investigated the principles, the characteristics, the components and the operation of solar chimneys in their review paper. They also gave a brief overview of the research about SCPP. which was categorized into three sections including the solar chimney projects, the numerical studies, and the unconventional solar chimneys until 2013. In 2014, Olusola Olorunfemi and Bamisile [14] presented a brief review of solar chimney, and limited the solar chimney applications to the desert prone villages with a foucs on the northern regions of Nigeria.

It is clear that previous review papers are incomplete: some are regional, some are not up to date, and the contents are not comprehensive. Considering the rapid development of this field, it is essential to conduct a timely and critical review that captures the latest development. A comprehensive and updated review is presented in this work to gather all the works and analyze the gaps for showing a roadmap for future researchers. This work includes the experimental studies, analytical and simulation works, the solar chimney applications, hybrid systems and geographical case studies, , as well as critical comments and suggestions for future work.

2. Review on experimental work

The first prototype solar chimney power plant with 50 kW peak power output was built by a German structural engineering company, Schlaich Bergermann [15] in Manzanares, around 150 km south of Madrid, Spain in 1981(Fig. 2). The plant had a solar chimney with 194.6 m height, 5.08 m diameter, 0.00125 m thickness of the metallic wall, and a collector of 122 m in radius with a PVC roof-cover, as well as a single-rotor turbine system equipped with four blades at the chimney base. The key characteristics of the Manzanares solar chimney are reported in Table 1. This prototype was in operation from 1982 to 1989 and the electricity generated was integrated into the local power grid. In 1983, Krisst et al. [16] built four pilot SCPPs, including a a "backyard-type" device with 10 m high chimney, 6 m collector base diameter and a power capacity of 10 W in West Hartford. Kulunk [17] built a micro scale power plant of 0.14 W with a solar chimney 2 m high, 7 cm in diameter and a 9 m^2collector in Izmit, Turkey in 1985.

In 1997, a solar chimney power demonstration model was built by Pasurmarthi and Sherif [18] in Florida, and two enhancements including extending the collector base and introducing an intermediate absorber were tried on the collector to increase the power output [19]. In 2002, a pilot solar chimney power of 5 W was built on the roof of a building by Zhou et al. [20], [21] in China. The pilot plant, which had 8 m tall chimney and 10 m collector diameter, was re-built several times for different purposes. A single sheet of transparent glass fiber reinforced plastic was used to cover the framework.

A pilot solar chimney system was constructed by Ketlogetswe et al. [22] in Botswana, in 2005, which had a glass reinforced polyester chimney with inside diameter of 2 m and height of 22 m with a collection base area of approximately 160 m^2. They observed that the maximum peak temperature was recorded after the maximum peak irradiation because the ground absorbed part of the incoming solar energy, which was later released. A prototype was built by Maia et al. [23] for the validation of their mathematical model and numerical methodology in Brazil in 2009. The authors assessed the effects of the basic geometric characteristics of the solar chimney on the function of the airflow based on the dimensions of the built prototype.

In 2011, a pilot of solar chimney was built by Kasaeian et al. [24], [25] in the campus of University of Zanjan, in Iran. A pilot of solar chimney with two-layered polycarbonate sheets, covered collector 10 m in diameter and a chimney with 12 m polyethylene pipe was constructed. According to the amounts of air temperature and velocity at different positions of the collector, the maximum air velocity, and the maximum chimney temperatures were obtained. The measurements showed that the air inversion at the bottom of the chimney appeared after sunrise on both cold and hot days, but by increasing the day temperature, the inversion effects were eliminated, and a steady air flow was created inside the chimney (Fig. 3). In 2011, a small-scale solar chimney was built by Najmi et al**.** [26] in Kerman, Iran. The authors studied effective parameters to optimize the solar chimney performance and performed an economic analysis. It was suggested that the usage of asphalt or rubber at the bottom of the collector, double glazing glasses on the roof of the collector, a decreased collector height to 1.3 m, and installation of conical shape at the entrance of chimney could increase the power output. For the purpose of improving the function, the effects of the collector diameter, and chimney diameter and height on the generated power in solar insolation of 800 W/m^2 were investigated by Gholamalizadeh et al. [27].

A solar updraft tower consisting of an air collector of 1.4 m in diameter and 80 cm tall chimney was constructed by Mehla et al.[28] in the NIT Hamirpur campus, Himachal-Pradesh, India, in 2011. The work reported that the solar chimney diameter of 8 cm gained the maximum velocity when the ratio of chimney diameter to chimney height was 0.1. The first pilot solar updraft power plant in Jordan was built by Al-Dabbas [29] (2011) and particular attention was given to the measurements of air velocity, temperature, solar radiation and voltage difference.

Bugutekin [30] built an SCPP in the Turkey's Southeastern Anatolia region to investigate the effect of the collector diameters on the air flow rate and temperature in the chimney. The results showed that with the increase of the collector area, the ground temperature increased and thus, the air temperature and air flow rate at the base of chimney increased quickly. Chappell et al. [31] designed and fabricated a small-scale solar chimney, aiming to achieve low material cost and minimal maintenance effort without the use of heavy machinery. An assessment of one likely location for this solar chimney was conducted in the Northern Mongolia during the summer of 2011. The original chimney dimensions were determined from the equation of power output by Haaf et al. [4], which is presented by Eq.(1).

$$N_{el} = \eta . \frac{2}{3} . g . \frac{H_T . \pi R_c^2 . I}{c_p . T_a} \tag{1}$$

An experimental study was done on an inclined passive wall solar chimney (IPWSC) by Khanal and Lei [32], in 2014. The heat flux of this model on the active wall was uniform, in the range of 100 W/m^2 to 500 W/m^2. It was found out that the velocity of air flow inside the air gap width significantly depended on the inclination angle. In 2015, Shahreza and Imani [33] designed and constructed a solar chimney with two intensifiers to intensify the sun's irradiance all around the solar chimney. It was concluded that the use of these intensifiers around the solar chimney caused air rising velocity and consequently increased the power generation considerably. A photo of the solar chimney and the intensifier is shown in Fig. 4.

Al-Azawie et al. [34] studied the potential of six ground materials in Malaysia, experimentally and numerically. These materials consisted of ceramic, sawdust, sand, dark green painted wood, black stone, and pebble which were used for converting solar radiation to kinetic energy. The results showed that black stone and ceramic had better function, in comparison to other materials. Ceramic has a better heat storage capacity but because of black stone's availability, it was suggested as the absorbing material in solar chimneys. Aja et al. [35] investigated the effect of wind speed and wind direction on the performance of an inclined solar chimney facing to the south. It was found that the wind speed had a great effect on the convective heat loss via the walls and the cover to the ambient.

The use of phase change material (PCM) could increase the thermal energy storage capacity of solar chimney, and extend the usage of solar chimney to night. In 2014, Li and Liu [36] studied the performance of solar chimney with PCM in three different heat fluxes: 500 W/m^2, 600 W/m^2 and 700 W/m^2, and it was found that for all the investigated conditions, the duration of the PCM application could exceed 13 hours and 50 minutes.

In 2014, the geometrical parameters of solar chimney were analyzed analytically and numerically by Kasaeian et al. [37] at University of Tehran, Iran. A mathematical model of solar chimney was investigated and validated with the experimental data. They found that the solar chimney with the collector inlet of 6 cm, chimney height of 3 m and chimney diameter of 10 cm had the best performance. In another work by them in 2015, a solar chimney with 2 m height and 3 m collector diameter was built and investigated. The air velocity and temperature distributions were evaluated and it was found that the solar chimney had a better performance at a reduced entrance size. It was also observed that air inversion didn't happen because of the changes in the geometrical parameters and ambient temperature [38]. In 2014, Tan and Wong [39] evaluated the effects of the ambient air velocity and the internal heat load on the thermal environment of the solar chimney ducts. They reported developing the air velocity in solar chimney for the ambient air speed higher than 2.00 m/s. In 2015, Okada et al. [40] used a diffuser tower instead of a cylindrical one to increase the velocity of the air in the turbine. The results showed that this model increased the air velocity approximately by 1.38-1.44 times and so the power output was reported as 2.6-3.0 times higher than the convectional cylindrical type. Figure 5 shows a schematic concept of their chimney.

In 2015, Nasirivatan et al. [41] studied the influence of the Corona wind on the performance of solar chimney. The results showed that the electrohydrodynamic force increased the absorber heat transfer coefficient and consequently, improved the output power of the solar chimney. Fig. 6 shows the experimental setup which was built in Tehran. The optimization of a pilot setup of solar chimney with 3 m height and 3 m collector was carried out by Ghalamchi et al.[42] in

2016. The temperature and velocity distribution with different geometry parameters and absorber material were analyzied to obtain the optimized values.

Table 2 shows a summary of the experimental studies in the investigated literature. Based on this table, the gap in the literature is analyzed, and these gaps will clarify the situations for the fields which have the opportunity for the future studies.

Gap analysis on the experimental work: The studies are mostly about simple small solar chimneys, and the number of studies is much smaller than hybrid systems carried out by modeling and simulation. . Many modifications and optimizations have been carried out, but it is needed to convert the simple systems to hybrids, obtain the optimum dimensional harmony between the chimney and collector dimensions, compare different sizes and optimize the systems optically. Also, there is a big gap for manufacturing and testing specified turbines for SCPPs. Many experimental works have been done without any investigation on turbine which is the main moving part of these systems. Many reports are available on the data of air velocity, temperature and the ideal output power, neglecting the presence of any turbine.

Among 40 reports on experimental works, there only a few reports are related to the large-scale solar chimneys, which call for more studies. .

3. Analytical and simulation studies

Weinrebe and Schiel [43] investigated and compared a solar chimney and a down-draught power plant. For the purpose of this investigation, a simple thermodynamic model was developed and the results showed that a solar chimney generated more electricity (i.e., three to five times) than a solar tower having the same chimney dimensions. Mullet [44] carried out a study to drive a comprehensive efficiency investigation of SCPP in 1987. For describing the chimney performance, the governing differential equations were derived and developed by Padki and Sherifto [45], [46] in 1988, and a feasibility study was conducted for different scaled power generation for the village situations, in 1989.

In 1999, Padki and Sherif [47] analyzed the performance of solar chimney by developing a single model. The equations of the available power and the solar chimney efficiency were obtained from the analytical model. The equation indicated the effect of various geometrical and operating parameters on the chimney performance. The error percentage in the predictions of the analytical model was shown to be in the range of 4-6%. Lodhi [48] in 1999 presented a comprehensive analysis of the chimney effect and efficiency. In addition the cost of a SCPP of 100 MW set up in developing countries was estimated based on the rate of annual energy production of 876 million kWh for 20 years for plants having chimney 1 km high and collector area of 2 km^2.

In 2000, Chitsomboon [49] stated that the plant efficiency was constant considering the tower diameter, the roof size, and the insolation level, and there was a linearrelationship between the power and the efficiency and the tower height. An analytical model with thermo-mechanical mechanisms for predicting the performances of a solar chimney was proposed by Chitsomboon [50] in 2001. The model was different, in significant ways, from the models proposed in the literature in which, it considered interactions of flow in the greenhouse and the flow in the chimney through the small pressure difference. In 2003, Dai et al. [51] analyzed some influential parameters, including the diameter of the solar collector, ambient temperature, chimney height, the efficiency of the wind turbine and solar irradiance, and showed that a non-linear increasing trend of the power output with the plant size.

For maximizing the electric power output for a fixed condition, the pressure drop at the turbine is a crucial factor. The pressure drop ratio in turbines was first reported as a value of 2/3 by Haaf [52] in 1984. In the later works, higher values of this factor were presented by Schlaich [5] in 1995 and Backstrom and Fluri [53] in 2006. Many research works have been mathematically done on the modeling of SCPP collector performance. A numerical model for the use of water-filled tubes on natural soil under the collector roof was presented by Kreetz [54] for thermal energy storage. His calculations showed the possibility of a consecutive day and night operation of the solar chimney. In 2004, the feasibility of using water-filled tubes on the collector floor as a heat storage device was investigated by Bernardes [55]. This technique helps to smooth out the heat requirement for the generation of warm air to drive the turbine and increases the power output after sunset. The effect of energy storage layer on flow was analyzed, and different mathematical models were established for the collector, the chimney and the energy storage layer by Tingzhen et al. [56], [57] in 2008. Fig. 7 shows that the heat storage ratio of the energy storage layer is higher than 80 %. It first decreases then increases, when the solar radiation increases from $200W/m^2$ to $800W/m^2$. Zheng et al. [58] investigated the effects of various energy storage materials on the power output at different solar insolations.

Hurtado et al. [59] developed a numerical modeling under transient conditions, based on the Manzanares pilot plant [5], to analyze the thermodynamic behavior and the power output of an SCPP over a daily operation cycle by considering soil as a heat storage material. Their results showed a significant increase in the output power when the soil compression was increased (Fig. 8). In the study of Daba [60], both the solar chimney power plants as the plants with and without thermal storage system were simulated for the case of a far region using Fluent and the effect of turbine position was analyzed. It was observed from the analysis that the plant efficiency would be improved by using thermal storage tanks.

In 2007, a thesis was done by Pretorius [61] to investigate and optimize a large-scale solar chimney. The author proposed a double-roof collector to improve the chimney function at night. The results showed that vegetation would cause major reductions in the plant performance. Bernards et al. [62] conducted a theoretical investigation of a solar chimney in steady state and natural convection conditions. Table 3 shows the mass flow rate in a variety of configurations for the horizontal to vertical transition section (HTVTS). A direct connection had the smallest air mass flow due to the appearing of the flow recirculation at the junction, and a curved junction produced the highest flow [63]. Kirstein [64] and von Backstrom [65] investigated the flow through the HTVTS of the solar chimney based on the evaluation in a scaled model, and carried out a CFD simulation with the CFX software. Since in the previous models the Reynolds number scale effect was not considered, the values of this simulation were smaller [66]. Kolb and Helmrich [67] suggested a geometry with bulky intake for the configurations with multiple horizontal axis turbine. They compared the single vertical-axis turbine with the multiple horizontal-axis turbine configurations for a 200MW SCPP by the CFD methodology. In 2006, Denantes and Bilgen [68] carried out a comparison for two counter-rotating turbines without guide vanes and with inlet guide vanes.

The performance of different layouts for the turbo-generator was compared by Fluri and Backstrom [69] using analytical models in 2007. These layouts included four configurations: single rotor turbine with guide vanes, single rotor turbine without vanes, a counter-rotating turbine with guide vanes and counter-rotating turbine without guide vanes (Fig. 9). In 2007, Tingzhen et al. [70] carried out numerical simulations on the chimney systems equipped with a

3-blade turbine. Also, the design and simulation of an MW-graded SC system with a 5-blade turbine was presented (Fig. 10).

Fig. 11 shows three configurations of a solar chimney power conversion unit (PCU) including a turbine with a single vertical axis, a multiple vertical axis and a multiple horizontal axis which were compared by Fluri and Von Backstrom [69] in 2008, who analyzed the performance of power conversion units with a simulation program that was described by Pretorius and Kroger [71] in 2006. In other works, the running losses of solar chimney turbine was guessed according to the losses of wind turbines [72], [73]. A mathematical model was introduced by them, for each loss element in PCU. Fig. 12 shows the schematic drawing of solar chimney power conversion units with multiple horizontal axis turbine configurations. They reported that the efficiency and energy yield of the single vertical axis turbine was slightly better. But its output torque is huge, making costly its drive train and questionable its feasibility [74], [75].

Gannon and Backstrom [76] developed an ideal air-standard cycle analysis to calculate all the thermodynamic variables depending on the chimney height, wall friction, additional losses, internal drag and area change. The developed analytical model showed good agreement with the experimental results of the small-scale plant built in Manzanares allowing it to be used reliably in the prediction of the output of a full-scale plant. Gannon and Von Backstrom [77], [78] investigated the performance of the turbine for SCPPs. They reported that the anticipated pressure drop in a full-scale solar chimney turbine was much higher than what had previously been forecasted. They also investigated the performance of the turbine using an experimental program and showed total-to-total efficiency and total-to-static efficiency of 85%-90% and 75%-80%, respectively. Later on, in 2004, von Backstrom and Gannon [79] presented analytical equations to show the influence of each coefficient on the turbine efficiency, designed the turbines of the solar chimney, and determined the preliminary turbine layout according to the turbine efficiency. A typical schematic turbine layout is shown in Fig. 13.

Von Backstrom and Fluri [53] analyzed the influences of the volumetric airflow on the chimney power output in different turbine working conditions and aerodynamic losses. The range of the pressure drop value that has been predicted from the analysis had an agreement with what which were predicted by other researchers. According to other studies, the pressure drops were about 0.83 [80], 0.7 [81] and 0.8 [82]. Therefore, no unified value of the factor existed but a range of values were suggested. Also, it is clear that the values were close to the value of 0.9 [83]. In

Table 4, similar comparisons for the data from Schlaich for several test cases are tabulated. It shows that the simple power law (PL) model predicts the maximum power flow (MFP) within 1% point compared to the maximum fluid power collector (MFP Coll.). The model was pessimistic in the prediction of the maximum fluid power value and optimistic in the prediction of turbine pressure drop. Backsrtom et al. [65] investigated the flow through a representative tall solar chimney with internal bracing wheels. The investigation determined coefficients of wall friction, bracing wheel loss, and exit kinetic energy in a model chimney, for both ideal non-swirling uniform flow and swirling distorted flow.

An air standard thermodynamic analysis for the solar chimney cycle was presented by Backstrom and Gannon [84]. In their study, simple equations were derived for the cycle efficiency ($\eta = g\Delta z/c_p T_2$), the power per unit mass flow ($P = g\Delta z \Delta T_{23}/T_2$), and the available turbine pressure drop ($\Delta p_t = \rho_3 g \Delta z \Delta T_{23}/T_2$). A thermal and technical study of solar chimney power system were presented by Bernards et al. [80] Regarding the power output versus time, it was found that the factor of pressure drop at the turbine was about 0.97 for obtaining the maximum power (Fig. 14). They indicated that this value of pressure drop was hard to reach. The value was expected to range from 0.8 to 0.9.

In 2010, Bernardes and Von Backstrom presented two designs of output power control for solar chimney. Volume flow and Turbine pressure drop were considered as the adjustable variables in numerical simulations. They have used the climatological input data of Sishen (Latitude S26.67 °), South Africa, which was reported by Pretorius [61] in 2007, and heat transfer coefficients which were presented by Pretorius et al. [85] and Bernardes [86] in 2007. The relationships between the x-factor (ratio of turbine pressure drop to the available system pressure difference), the power output, the volume flow rate, and the temperature increase in the collector were reported[87].

A detailed theoretical model was developed by Koonsrisuk and Chitsomboon [88] in 2010, to evaluate the performance of solar chimney power system. They presented the operating range of the turbine and showed that the plant size, the factor of pressure drop at the turbine and the solar heat flux were the important parameters for the performance enhancement. In 2010, Nizetic and Klarin [89], with a simplified analytical approach, reported that the turbine pressure drop factors were in the range of 0.8–0.9 for SCPP. Fig. 15 shows the impact of ratio $\boldsymbol{\alpha/\beta}$ on the pressure drop factor, where **α** is the effective absorption coefficient and **β** is the factor proportional to the convective energy loss (W/m^2 K).

Schlaich [90] designed a reinforced concrete cylindrical SC with 1000 m-height and 170 m-outer diameter for the commercial SCPPs. He designed and installed some elements to hold the shell and enhance the buckling stiffeners of the solar chimney structure. Changing the thickness of the shell from 2 m at the bottom of the chimney to 0.25 m at 1000 m height was designed by Harte and Van Zijl [91]. For a 200 MW plant with 1500 m height solar chimney, the thickness of the shell remained fixed at the heights higher than 1000 m. A serial of hyperbolic solar chimneys in the range of 500 m to 1500 m was designed by Backstrom et al. [92]. For the purpose of effective reducing the turbulent friction losses, a new collector concept having branched ribs was proposed by Bonnelle [93] in 2004. Pasumarthi and Sherif [94] suggested a design of top-installed turbines for solar chimney. A comparison between the air flow static pressure of the chimney base and the top was carried out by Bonnelle [93]. It was reported that negative pressure and relative positive pressure were appeared in the solar chimney when the turbine was installed at the base and the top of the solar chimney, respectively.

Sangi et al. [96] in 2011 presented two numerical simulations for the geometry of the Manzanares prototype. They compared their results with the experimental data of the Spanish prototype [4] and the results of Pastohr et al. [95]. The results suggested that the simple two-dimensional axis symmetric simulation could be utilized for engineering calculations. Pastohr et al. [95] numerically solved the complicated Reynolds-averaged Navier-Stokes equations (RANS) for the upwind power plant by using FLUENT, and compared their results to another simple model in 2004.

Pretorius et al. [97], [85] developed a numerical model in 2004. They considered a large-scale solar chimney power plant as a reference and simulated its performance. The results showed the temperature distributions in the ground under the collector, the variations in the seasonal generation, and the total annual electrical output. A convective heat transfer equation was developed by Pretorius and Kroger in 2005 to evaluate the influence of various equations and other variables on the performance of an SCPP. They numerically presented that the collector roof shape and inlet height effect on the power generation and the results of the models using limestone and sandstone soil were similar to a granite-based model (Table. 5). Also, the turbine inlet loss coefficient was increased only by 0.6% in the annual plant power production, while using better quality glass increased the annual plant power output by 3.4% (Fig. 16) [66].

In 2006, Ming et al. [98], [99] developed a mathematical model to assess the function of a SCPP. They investigated the influences of different parameters on the power output and efficiency, driving force and the relative static pressure. The threshold values of the temperature ratios (τ), the ratio of the difference between the collector surface temperature and the temperature at the turbine $(T_S - T_H)$ to the difference between the air mass temperature under the roof and the collector surface temperature $(T_M - T_S)$ were found by Onyango and Ochieng [100] in the rural areas of developing countries in 2006. Fig. 17 displays that with increasing the length L of the collector surface and reducing the height H or radius R of the turbine, the power generated by the solar chimney power plant is increased.

Zhou et al. [101] compared the measurements of their experimental investigation in 2002 with a mathematical model in 2007. They found that the simulation could predict the performance of the pilot equipment well, and was feasible to different scales of solar chimney thermal power generating systems. In 2007, Koonsrisuk and Chitsomboon [102] carried out numerical simulations of solar chimneys by the use of dimensionless variables and a CFD code for the purpose of experimental design of a small solar chimney. They reported that for the same solar heat flux, all dimensional diameters stay unchanged, except the roof radius. In fact, they carried out a study to keep the dynamic resemblance of a prototype with its simulations at the same solar insolation, because of the difficulty of conducting a practical work by using changeable insolations with different physical models [103].

A numerical simulation was done using the Spanish prototype plant by Huang et al. [104] in 2007. The Boussinesq model and the Discrete Ordinate radiation model (DO) were adopted for natural convection and radiation, respectively. The main boundary conditions are shown in Table 6. They concluded that the increase of solar radiation intensity increased the temperature difference between the inlet and outlet of the collector and the differential pressure of the collector-chimney transition section. The effect of inclined angle on the output of a solar chimney power plant system was investigated by Sun et al. [105] in 2007. An unsteady two-dimensional axis symmetric numerical simulation for 1 km chimney height and 2.5 km collector radius was studied by them. They found that decreasing the inclined angle increased the output of the system and velocity was not increased clearly with increasing the heat flux in the wall. In

2008, a theoretical analysis of a turbulent flow inside a solar chimney was presented by Maia et al. [23] and the finite volumes technique was used in generalized coordinates.

Zhou et al. [106] reported the maximum chimney height in the atmospheric pressure from 90 kPa to 101.3 kPa for preventing negative buoyancy at the chimney end. They examined the effect of collector radius and different lapse rates of outdoor temperatures on the maximum chimney height (Fig. 18). In 2009, the thermodynamics of a simplified model of SCPP was studied by Petela [107]. Some assumptions were considered to simplify the thermodynamic model. In this study, the distribution of solar input between the SCPP components based on the energy and exergy balances was determined by the energy and exergy flow diagrams. An exergetic and energetic analysis of solar chimney airflow was conducted by Maia et al. [110]. For doing this study, they built a prototype in Belo Horizonte (Brazil). The chimney height was 12.3 m, and the collector diameter was 25 m. They developed a model with the balance equations using other literature [108], [109]. Other results showed that the exergy amounts were greater at a constant temperature (minimum ambient temperature) of the dead state (environment reference) in comparison with varying temperature (ambient temperature).

In 2009, Koonsrisuk and Chitsomboon [111] established a dynamic similarity between a prototype and its scaled models with combining eight primary variables into one dimensionless variable. Three physical configurations of the plant (fully geometrically similar, partially geometrically similar and dissimilar types) were tested numerically by them for similarity. Ninic and Nizetic [112] proposed the idea of replacing chimney with a vertical gravitational vortex column, in 2009. A simplified analytical model of the idea was developed, and the numerical solution was presented. In 2009, Zhou et al. carried out numerical simulations of solar chimneys using CFD program with a developing model including three-dimensional (3D) Steady Navier–Stokes equations in the Cartesian coordinate system to evaluate the performance of a compressible flow through a solar chimney. The solutions of the equations carried out in this work were based on the algorithm SIMPLE proposed by Patankar [113]. Pressure term was discretized with a second-order scheme, while the density, momentum, and energy equations were discretized with a second-order up-wind scheme by Zhou et al. [114]. They found that their model was more précised than the Boussinesq model and the full-buoyancy model when using some commercial CFD programs.

In 2009, Bernardes et al. compared the methods which were used in the Bernardes and Weinrebe [80] and Pretorius and Kroger [71] studies. They concluded that the greater heat transfer coefficients from the roof and ground to the flow with the Pretorius method caused lower losses from the roof, higher heat transfer to the flow and lower collector inside temperature. Fig. 19 shows the simulated mass flow and daily power output based on the monthly average climatic data of June and December [115].

Chergui et al. [116] in 2010, analyzed a natural convection laminar heat transfer case occurring in a chimney. The fluid dynamic and the heat transfer of the air flow with an axisymmetric system were tested by them in a dimensionless form. Fig. 20 displays the scope of the study and the boundary conditions. The results showed that for most Rayleigh numbers, the flow stayed laminar except for Raleigh number of 10^8 due to the existence of some disturbances. Xu et al. [117] carried out airflow numerical simulations and obtained the power output of a solar chimney connected to the storage layer and turbine same as the Spanish prototype. They reported that the output power of the system reached to 120 kW when the solar radiation was 600 $W/m^2$and the turbine efficiency was 80%.

Bouhdjar et al. [118] simulated the airflow inside an axisymmetric chimney for the purpose of analyzing the thermo-hydrodynamic behavior of the system. Particular consideration is taken in case of utilizing natural convection heat transfer problem happening in SCPP in the laminar region. Koonsrisuk and Chitsomboon [119] carried out a mathematical modeling to evaluate the performance of solar chimney power plants. This study indicated that the solar heat flux, the turbine pressure drop and the plant size were the significant parameters for enhancing the system performance. This paper also proposed the relatively simple method primarily to evaluate the turbine power output for solar chimney systems. Table 7 indicates good agreement between the theoretical and the experimental results [52]. A mathematical model based on the continuity, momentum, energy, and state equations was developed for a sloped solar chimney system by Koonsrisuk [120]. The results showed that using a near-unity ratio of the collector inlet flow area and the collector exit flow area caused a strong wind which might carry a lot of surface dust and cause noise pollution. Fig. 21 shows that the temperature rises across the collector with increasing the collector area. Table 8 shows that the flow velocity increases with the chimney height.

Koonsrisuk and Chitsomboon [121] worked on a theoretical model using CFD analysis to investigate the effects of flow area changes on the potential of SCPP. In this study, they examined the flow area changes in collector and chimney (Fig. 22). Koonsrisuk [122] investigated the performance of SCPP based on the second-law analysis. A comparison between a straight solar chimney and a sloped solar chimney was performed in this study. The results revealed that the system height had a positive effect on the second-law efficiency of both systems (Fig. 23).

Lorente et al. [123] used a constructal design to increase the efficiency of solar chimney power production on an available land area. They found that the power generated per unit of the land area was proportional to the length scale of the power plant, the chimney height, the roof radius, and the chimney radius. Also, Koonsrisuk and Chitsomboon studied the influences of roof diameter, roof height, chimney height, chimney diameter and solar irradiance on the performance of the solar chimney by using and comparing five simple theoretical models and CFD simulation in 2009. These five theoretical models were of Chitsomboon [50] in 2001, Schlaich et al. [82] in 2003, Tingzhen et al. [98] in 2006, Zhou et al. [106] in 2009, and Koonsrisuk and Chitsomboon [111] in 2009. Figs. 24 and 25 show the effects of the tower radius and roof radius variations on the plant performance, respectively [124].

For the purpose of increasing the power generation, Koonsrisuk et al. [125] in 2010 described the constructal-theory for the solar chimney geometry. They managed to determine the maximum power and the maximum flow rate based on a simple model. The height/radius ratio was determined according to the constructal theory of Bejan et al. [126] in 2008. They demonstrated that the pressure drop at the collector inlet and also at the transition section between the collector and the chimney were insignificant. Li. J-y et al. [127] evaluated the influences of collector radius and chimney height on the power output of SCPP using a theoretical model that has been verified by the experimental data of the Spanish prototype. The theoretical power output of an SCPP was reported to be directly proportional to the collector radius and chimney height in Fig. 26 and Fig. 27, respectively.

Ming et al. [128] analyzed the impact of three different chimney configurations based on some constraints such as equal chimney bottom section area or same chimney surface area, upon the chimney outlet air temperature and velocity, system output power and efficiency. Ninic [129], in 2006, analyzed different types of collector with dry and humid air. The impact of the air humidity on increasing the operating potential and efficiency of the whole plant has also been analyzed. So, it was found that the height potential will be considerably increased if the air at the collector is moistened.

Hamdan [130] evaluated the use of constant density assumption across solar chimney and compared it with a more realistic chimney mathematical discrete model that allows density variation across the chimney. Fig. 28 shows that using constant density across the chimney will over predict the power generation by less than 20% at the chimney height of 1000 m. Also, it is found that for a fixed power generation, as the chimney height increased, the collector diameter should be increased (Fig. 29). Ming et al. [131] conducted a numerical analysis on the performances of an SCPP identical to the prototype in Manzanares [15] to investigate the impact of a strong ambient crosswind on the system output power through the collector inlet and chimney outlet. The results showed that when the ambient crosswind was comparably weak, it would deteriorate the flow field and reduce the output power of the SCPP. Also, it may even increase the mass flow rate and output power if the crosswind was strong enough (Fig. 30).

Zhou et al. [132] presented a model of correlating atmospheric cross flow and the fluid flow inside a solar chimney system that considered the airflow in SCPP as a compressible fluid. Their achievements showed that the atmospheric cross flow had a significant influence on the SCPP inflow, and the SCPP inlet air velocity approximately equaled to 26% of the cross flow velocity. Fig. 31 shows that the pressure potential and the SUT inlet velocity increase with increasing the cross-flow velocity. The special climate, which appears round a commercial solar chimney by the warm air flowing from the chimney outlet, was analyzed by Zhou et al. [134] in 2008, using the Bosanguet equations [133].

Zhou et al. made a 3D numerical simulation model to investigate the plume in an atmospheric cross-flow from an SCPP. This model was validated by comparing the calculated data with the numerically simulated results for one-dimensional buoyancy-driven compressible flow in a proposed 1500 m high solar chimney with an inner diameter of 160 m that had been carried out by Backstrom and Gannon [135]. They showed that with an increase in the chimney height, the temperature of the outflow decreased due to more thermal energy being converted to gravitational potential energy [136]. In 2009, Van Reken and Nenes [137] conducted a simulation of the plumes of large-scale SCPP using a cloud parcel model. This model showed that cloud would probably be formed within the SC, with precipitation formation possible in some cases.

Panse et al. [139] suggested geometry of "Inclined Solar Chimney" (ISC) which was constructed along the face of a high rising mountain in 2011. The basic concept was investigated by Bilgen [138] in 2005, and the efficiency of the collector was analyzed. They reported that an ISC of width 2632 m, thickness 5 m, and height 200 m could produce 1 MW output. The wind velocities at the top of the hill enhanced the velocity of the emerging air draft so that this structure could control both the solar and the wind energies. The influence of different slopes on receiving insolation was analyzed by Jing et al. [140]. They also studied the optical slope of the collector in solar chimney power plants. The results showed that with a suitable slope of the collector, the incidence angle decreased. Therefore, the insolation increased on the solar chimney. Zhou et al. [141] investigated a new design for a large solar collector around hollow space on a mountain in the region with steady geology. The vast space in the mountain was hollowed out as an updraft solar chimney which was safe and economical. Fig. 32 gives a vertical view of the prototype. Zhou and Yang [142] presented a new SCPP with floating chimney which was made on a mountain-side, section by section in 2009. In this structure, the inclined face of the mountain functioned like the chimney with a solar collector.

Papageorgiou [143] performed some works on a floating solar chimney (FSC) power plant such as the optimum design of SCPP. He found that the floating chimneyes were 4 to 10 times smaller and 5 to 6 times cheaper than the concrete solar chimneys (CSCs) [144]. Papageorgiou [145] performed a scale analysis for FSC and showed that the direct production cost of the FSCs was decreasing, while their dimensions and rating power were increasing. He also presented the efficiency and power output of a solar turbine power station using floating solar chimney. The effectiveness with a nominal power output of 100 MW was in the ranged of 4.5% to 7 % [146]. Papageorgiou [147] in 2004 investigated the external wind effect on FSC. He expressed that the FSC might be destroyed because of its accordion type folding lower part and base construction. In 2005, Papageorgiou [148] studied generators and turbine for the FSC power plant. In this study, the Doubly Fed Induction Generators (DFIGs), with small electronic control units, were examined as the best and most economical solutions. Also, he studied the basic performance equations of solar turbine power station (STPS) [149]. The examination of multi-pole generators connected to floating solar chimney was also carried out by Papageorgiou et al. [150]. Ahmed et al. [151] proposed a new design of virtual height aided solar chimney that increased the efficiency of solar chimney due to the virtually mimic larger heights of the chimney.

Zhou et al. [152] carried out an economic investigation of FSC power plant. They analyzed the cash flows of a 100 MW plant through the entire service period. Also, they analyzed the influence of the factors including an interest rate of loans, inflation rate, sale price of electricity, non-returnable rate and income tax rate on the cash flows of a 100 MW FSCPP sensitivity. Also, a mathematical model of the techno-economic evaluation of solar chimney power plant was developed by Al-Dabbas[153]. In 2009, an alternative cost model was developed for large-scale solar chimney power plants by Fluri et al. Also, they compared three previous cost models for large-scale solar chimney power plants, which were presented by Schlaich in 1995[15] and Schlaich et al. [154] in 2004. The effect of carbon credits on the levelised electricity cost (LEC) was investigated by Fluri et al. [155], and it was found that carbon credits reduced the LEC for an SCPP.

A TRNSYS program was developed by Cao et al. [157] for analyzing the performance of SCPP. In this model, the nightly power production was not considered and needed to be developed further. The results have good agreement with the results reported by Larbi et al. [156] at the same solar irradiance and ambient temperatures. Gua et al. [158] made a three-dimensional model to evaluate the solar chimney performance. Their results show edthat increasing the ambient temperature caused a negligible rise in the air temperature in the collector, but had an evident negative effect on the updraft velocity (Fig. 33). Yan et al. [159] analyzed the temperature distribution in the collector of a solar chimney to evaluate the effect of collector radius and turbine pressure drop on the efficiency of solar chimney. They found the optimum pressure drop in which the solar chimney had the highest power output.

Arefian et al. [160] studied the optimization of the collector's dimensions of a solar chimney with the entropy generation minimization technique. They demonstrated that the irreversibility which is caused by heat transfer, was significant in the solar collector, and the presence of chimney had a small effect on the total entropy generation. Guo H.J. et al. [161] presented a heat transfer and flow model of SCPP to analyze the heat storage performance of the system. Their numerical simulation demonstrated that various specific heat capacities, different thicknesses of heat storage layer and thermal conductivity of heat storage medium influenced the power output and generation stability considerably. Therefore, they decided to optimize these factors.

Guo P. et al. [162] carried out a study about the effect of solar radiation heat transfer and turbine pressure drop on the performance of SCPP. They found a significant effect of radiation heat on the heat transfer process in the collector. Dhahri et al. [163] studied the performance of SCPP using the steady state Navier-Stokes and energy equations in the cylindrical coordinate system. They also evaluated the influences of geometrical parameters of the collector on the performance of solar chimney. Zhang et al. [164] performed an analysis of solar chimney which was combined with the underfloor air distribution (UFAD). They studied three types of solar chimneys based on hot and cold aisles. The results showed that all types of solar chimneys had excellent potential in improving the airflow and temperature distribution. El-Rab et al. [165] carried out a thermodynamic analysis of solar chimney and studied the parameters that most affected the performance of the system. Castro Sliva et al. [166] analyzed the effect of geometric configurations on the flow conditions and the exergetic efficiency of a small solar chimney. The results showed that the most important parameters of the solar chimney were the collector diameter and the chimney height that significantly influenced the performance of solar chimney.

Azeemuddin et al. [167] studied a new technique utilizing waste heat energy in the form of flue gasses. They found significant improvement in the solar chimney performance. Xu et al. [168] carried out a numerical study on a solar chimney to 1 km height and 2 km radius to create multi-climate conditions inside the collector of the solar chimney power plant in China. Buonomo et al. [169] did a numerical study of a solar chimney system in the south facade of a building. They analyzed the effect of the height and spacing of solar chimney to improve the energy efficiency of the system. In 2014, a new, different model of solar chimney as a reinforced concrete solar chimney power plant (RCSCPP) was constructed and analyzed by Weibing et al. [170] in China. By evaluating the cost-benefit of the system, they demonstrated that the RCSCPP had more advantages than the coal-fired power plants. In 2014, Khanal and Lei [171] studied and analyzed the air flow behavior caused by natural convection in a solar chimney for evaluating the ventilation performance. The results showed that the mass flow ventilation performance for all flow regimes directly relates to the Rayleigh number. In 2015, they carried out the buoyancy induced convective flow analysis in an inclined passive wall solar chimney (IPWSC) stuck in a room. They evaluated the system performance for different passive wall inclination angles and Rayleigh numbers. The results showed that this system had a significant role in improving natural ventilation. They also found the optimum inclination angle [172].

Patel et al. [173] optimized the geometry of the important sections of solar chimney to improve its performance, using the ANSYS-CFX software. The collector inlet opening, the collector outlet diameter, the divergence angles, the chimney inlet opening were changed, while the collector diameter and chimney height were fixed. Lebbi et al. [174] studied the effect of geometric parameters of solar chimney as the energy source of hydrogen generating station (HGS). They evaluated the behavior of air flow inside the solar chimney and demonstrated that the tower dimensions have a great influence on the hydrodynamic control of the solar chimney. Analyzing an inclined roof-top solar chimney was an interesting work which was done by Al-Kayiem et al. [175] by studying the effects of the collector dimensions and chimney height on the system.

Gholamalizadeh and Kim [176] studied the greenhouse effect on the natural convection heat transfer characteristics in solar chimney. They used unsteady CFD model for analyzing SCPP. Also, they used the discrete ordinates (DO) method to solve the equations of radiation heat transfer. They demonstrated that simulation of the greenhouse effect had an important role in evaluating solar chimney performance. They also worked on another project, as optimization of the expenditure, total efficiency, and power output of an SCPP. They used the multi-objective genetic algorithm to find the best chimney height, chimney diameter and collector radius. They found that the increase in the power output was higher than the increase in the expenditure of the optimal configuration [177]. Guo et al. [178] simulated a new model for a solar chimney power plant that included the solar load, turbine models, and the radiation. Then they evaluated the influences of turbine pressure drop, ambient temperature and solar radiation on the performance of the system. The results showed that the effects of turbine pressure drop and solar radiation on the SCPP performance were so noticeable.

In 2014, a multi-objective optimization of solar chimney dimensions was carried out by Dehghani and Mohammadi [179]. They considered the capital cost and power output of the system to be minimized and maximized, respectively. For obtaining the results of optimal designs, a set of multiple optimum solutions as the Pareto frontier was utilized. They found this optimization method very effective and useful. Naraghi and Blanchard [180] carried out a model for time-dependent analyzing of the three parts of solar chimney including absorbing plate, cover glass, and air-gap. The results showed that the increment of the thermal mass of the absorbing plate caused higher airflow rate in the late and early times. The important properties of absorbing plate like specific heat, height, thickness and density can be used to increase its thermal mass.

In 2014, Liu and Li [181], [182] studied the thermal performance of a solar chimney which was integrated with the phase change material (PCM). They analyzed the PCM behaviors during its melting and solidification processes, absorber surface temperature, mass flow rate, and inlet and outlet air temperature difference. They also studied the system performance under different heat fluxes from 100 to 800 W/m^2 and found that when heat flux was equal or lower than 500 W/m^2, the system performance deteriorated strongly, but when it was higher than 700 W/m^2, there was not obvious improvement in the system performance.

The literature of this section may cover the categories of numerical, simulation, exergy analysis, CFD analysis, dimensional analysis and feasibility studies. According to what have been done so far, a summary of the previous works are tabulated in Table 9 and the gaps analysis is presented in the following statements.

Gaps on the analytical and simulation studies: Nevertheless many aspects of design, optimization, exergy analysis and dimensional analysis have been covered by the researchers in the last 30 years, there are still obvious gaps in these fields:

- For completing a comprehensive research project, experimental set-ups are recommended besides the theoretical studies on solar chimneys. A considerable amount of the studies suffers from lack of experimental validation. The main experimental system to which most of the works referred is the Manzanares power plant, which was built about 30 years ago. For that time, it was excellent, optimized, and up to date. But now, after passing 30 years, we still see that many researchers verify and validate their theoretical works with that plant.
- There are some gaps on exergy and exergo-economic analyses. The thermodynamic side of solar chimneys should be more focused considering the turbine characteristics.
- The algorithmic optimizations are applied for many energy systems. Here, for solar chimney researches, we can propose some algorithms like PSO, NSGA, firefly, ant colony, MDO and the hybrid methods.
- Due to the distinctive decrease of cost in the large-scale systems and the non-economic nature of small-scale chimneys, the economical aspect of solar chimneys is of much

significance. This important subject has not been covered completely, and there is no comprehensive economic report for the solar chimney power plants.

- Few dimensional analyses exist for small chimneys, and some are reported for large systems. There is no bridge to connect the micro, small and large scale solar chimneys. So, there is lack of a comprehensive program to predict the power output by changing the dimensions and slopes.
- More studies are needed on solar chimney simulations using the TRNSYS software.
- Simulation of hybrid solar chimney power plants with other renewable energy systems and fossil fuels power plants is another subject that has the situation for more works.
- The gaps are related to CFD of hybrid solar chimney systems and lack of variety in the validation references. Using the ANSYA CFX and COMSOL software are recommended; the potential of this software are higher than FLUENT.
- The decision-making methodologies are suggested for better deciding on installing solar chimney power plants. Also, there is a big gap for feasibility study of large (more than 10 MW) power plants.

4. Hybrid solar chimney systems and special applications

Zuo et al. [183], [184] built an integrated small-scale solar chimney power generation with sea water desalinization system to simulate the comprehensive system in 2011. They found that the maximum temperature difference between the heated air flow and the ambient temperature was 15°C, and the solar energy utilization efficiency was larger than 21.13%. Fig. 34 shows the schematic diagram of the integrated system. Yiping et al. [185], [186] proposed a hybrid solar chimney with seawater desalination. Electric power from water generators, power from the air turbine generators and fresh water were the products of the system. Zhou et al. [187] in 2010, conducted a comparison between a conventional SCPP and a hybrid system with water desalination. They reported that the power output and the air flow rate of the hybrid system were less than that of the classic solar chimney power plant.

Maia C.B. et al. [188] presented a practical study of the airflow through a solar chimney. They built a prototype on the campus of Universidade Federal de Minas Gerais, in Brazil, for the purpose of drying the agricultural products. The solar chimney was built with 1 m diameter and 11 m height tower which was supported by six mechanical tubes 1.3 m above the ground. The diameter, the height, and the height at the edge of the collector were 25 m, 0.50 m, 0.05, respectively. In this work, the climatic conditions were studied to evaluate the function of the solar chimney.

Ferriera A.G. et al. [189] studied the feasibility of a solar chimney to dry agricultural products. A solar chimney dryer is composed of an open-edge transparent circular collector which is connected to a tubular tower at the center (Fig. 35). For the purpose of evaluating the practical feasibility of this drying equipment, a prototype solar chimney was built in Belo Horizonte, Brazil. After making the device, the air velocity, and the climatic parameters were measured as the functions of the solar insolation. This solar chimney, with a tower height of 12.3 m and collector diameter of 1 m, was made by wooden sheets and covered by fiberglass. An experimental investigation of the performance of a solar crop dryer with solar chimney and no air preheating was described by Afriyie J.K. et al. [190] in 2008. The chimney was of a rectangular cross-section of width 440 mm, uniform gap of 80 mm and height of 625 mm. The results show that the solar chimney can increase the airflow rate of a direct-mode dryer especially when it is well designed with the appropriate angle of the drying-chamber roof. In 2014, Chen and Qu [191] developed a solar chimney-based drying system with the porous absorber and evaluated the heat transfer and flow in the system. They also considered the effects of the absorber tilt angle and the height of drying system on the heat transfer of the solar dryer.

Papageorgiou [192] presented a modular solar collector. These modular solar collectors are low-cost alternatives of the conventional collectors. The efficiency of the modular solar collector made of a series of triangular warming air tunnels with double glazing transparent roofs is estimated to be even higher than 50%.

Hao et al. [193] used a solar chimney to make natural ventilation. They studied the interior velocity in the solar chimney with vertical panels with 2000 mm height and 1000 mm length. They found that the airflow rises and the air velocity decrease when the chimney gap increases, and with developing of radiant solar intensity, the airflow, and air velocity increase. In 2015, Liu et al. [194] studied the effects of applying chimney on a solar hybrid double wall which was used for natural ventilation and buildings air heating. They evaluated various chimney wall gaps and radiation fluxes. The results showed that the airflow rate raised continuously with increasing the wall gap, but they didn't find the optimum wall gap. Their achievements also demonstrate that flow inversion occurs in the solar chimney with a gap width-to-height ratio bigger than 0.3. Jing et al. [195] constructed a solar chimney with the large gap-to-height ratio from 0.2 to 0.6 on a single wall and evaluated its performance in various chimney gaps and heat fluxes. It is observed that when all the conditions except chimney gap are fixed, by increasing the chimney gap, the maximum airflow rate is reached at the chimney gap of around 1000 mm, which is the optimum chimney gap in the variety of the chimney gaps considered in this work. Song [196] studied the ventilation performance of solar chimney in Japan. He examined the relation of the inlet and outlet, the connection conditions of the chimney shaft and the chimney and the solar radiation heat-receiving chimney area.

In 2015, an experimental and numerical model of a solar chimney was carried out by Imran et al. [197] in Iraq for ventilation and cooling a single room. They measured the temperature of the chimney's glass cover, the absorbing wall, and the induced air and analyzed them considering the induced air velocity. Exergetic analysis of solar chimney used in buildings for improving natural ventilation was done by Marigorta et al. [198] in Spain in 2015. The thermal and dynamic behavior of the fluid inside a solar chimney was evaluated with a three-dimensional CFD model. The results showed that the thermal efficiency is 0.55%, and the exergetic efficiency is 0.0006%. Because of these low efficiencies, they stated that solar chimneys as natural ventilation systems had small efficiency performance.

Natural convection in the air in a convergent chimney was studied by Buonomo et al. [199] With the purpose of improving the energy efficiency of the system, the fluid dynamics, and the thermal behaviors were studied. They found that these parameters directly rely on the chimney geometry. The results also showed that solar chimney is suitable for building heating in winter. Chung et al. [200] carried out a study on a solar chimney in a terrace house for improving the ventilation performance of the indoor environment. They obtained the optimum length and width gap of the solar chimney; therefore, they could receive the optimum chimney air velocity and thermal performance in the indoor space.

In 2003, Golder [201] built an SC 8 m high and 0.35 m in diameter joining with a solar pond of about 4.2 m diameter and 1.85 m depth in Bundoora in Australia. The tower was constructed from flexible circular ducting, and it was supported by the structure of a small experimental air generator tower. Water to air heat exchanger was used in the prototype chimney. A heat transfer rate of 1 kW was calculated from the mass flow rate of the brine and its temperature drop across the heat exchanger. Sampayo [202], in his simulation, proposed the use of a multi-cone diffuser at the top of the chimney to allow the operation as a high-speed chimney and to perform as a draft tube for any natural wind blowing, in 1986. Ming et al. [203] investigated the decrease of fluctuation factor of output power in SCPP using a novel hybrid energy storage system made of water and sandstone. The results show that using the hybrid energy storage of water and sandstone decrease the fluctuation factor of SCPP output power

In 2008, Davey [204] presented a concept for applying solar ponds for solar chimney thermal storage for the purpose of generating power during cloudy day and night time. A power plant combined with solar pond was analyzed by Akbarzadeh et al. [205] for the production of power in salt affected areas in 2009. The solar pond had an area of 60,000 m^2 and 3 m depth with a 200 m tall chimney of 10 m diameter that was operated in the northern parts of Victoria in Australia. Fig. 36 shows two combinations of the SCPP with a solar pond for generating electricity with two types of heat exchangers (direct contact and non-direct contact). The works that had been done in the performance enhancement of SCPP were reviewed, and the alternative techniques for enhancement of SCPP performance were presented by Chikere [11] in 2007. Geothermal/Solar chimney power plant and Hybrid Geothermal/PV/Solar Chimney power plant were proposed for prospective SCPP in the south region of Libya.

The solar cyclone is a means of extracting fresh water from Earth's atmosphere that was introduced by Kashiwa et al. (Fig. 37) [206], [207]. This solar cyclone could produce not only electric power but also fresh water. They investigated the feasibility of the solar cyclone using a theoretical model of a solar cyclone 500 m high and 42 m in diameter. The results showed that by assuming a separation efficiency of 80%, the solar cyclone can produce an annual power output of 3 MW and annual freshwater production of 2×10^6 tons in an arid region [206]. Kasayapan [208] investigated the mechanism of natural convection inside the inclined solar chimneys incorporating an electro-hydro-dynamic (EHD) effect induced from wire electrodes by numerical simulations. The schematic sketch of natural convection inside EHD solar chimney is illustrated in Fig. 38. Also, according to Fig. 39, the optimum inclined angle which obtains the maximum volume flow rate and heat transfer is found to be at $\theta = 60°$.

Since the solar chimney performance depends on solar radiation, its discontinuous operation is an inevitable problem. In 2014, Fei Cao et al. [209] used low-temperature geothermal water for the solar chimney to solve the problem mentioned above (Fig. 40). An experimental study of a hybrid geothermal cooling system was carried out by Yuebin et al. [210] in 2014 (Fig. 41). They coupled the system with an earth-to-air heat exchanger and a solar collector enhanced solar chimney. Three different tests were done as the active tests with forced airflow, a passive cooling test with natural airflow, and another passive cooling test was conducted. It is found that the mentioned system in the natural operation mode, can supply cooling without consuming any electricity and the solar chimney can increase airflow to the system in the daytime with high insolation. Haorong Li et al. [211] showed that this coupled system can provide great energy reserve in buildings and decrease the peak electrical demand in the summer time. The solar chimney transfers a volumetric amount of 0.28 m^3/s outdoor air into space. The earth-to-air heat exchanger can produce a maximum 3308 W total cooling capacity in a day.

In 2015, Zou and He [212] developed a hybrid cooling tower-solar chimney system (HCTSC) that includes a solar chimney with a natural draft dry cooling tower to produce electricity and dissipate waste heat. It is found that the HCTSC system can generate much more power output of turbine in comparison to a common solar chimney with the same dimensions. A cheap and efficient way for producing renewable energy was presented by Ozdemir et al. [213] in 2015 in Turkey. They showed an experimental wind chimney equipped with a thermoelectric generator. This system contains four components: a heat pipe for solar heating, a wind chimney for space cooling and ventilation, a thermoelectric (TE) module for electricity generation and some measurement devices and sensors. They found out that adding more TE modules would result in increasing output power, voltage, and electrical efficiency. Ghorbani et al. [214] designed a solar chimney with a dry cooling tower to improve the thermal efficiency of the Rankine cycle of a typical steam power plant. This study is mainly deliberated to the Shahid Rajaee 250 MW steam power plant of Iran. The result showed that the thermal efficiency of the fossil fuel plant increases up to 0.53%.

A designed Trombe wall in combination with solar chimney and water spraying system (Fig. 42) was presented by Rabani et al. [215] in Yazd (Iran) with the desert climatic conditions. The results indicated 30% increase in the thermal efficiency with water spraying system. Mareeswaran and Gopal [216] designed and constructed a solar cooling chimney (SCC), which is in a rectangular form. The mentioned system can prepare a passive way for cooling solar photovoltaic in solar power plants due to overcoming its operating temperature increasing and low efficiency.

Gaps on the hybrid systems and applications: Around 40 papers were reviewed in this section for the purpose of demonstrating what have been done so far and clarifying what may be proposed for the studies in the future. The preliminary solar chimneys were chimney-alone systems which were investigated for obtaining power. In the current years, some efforts have been done for combining the solar chimneys with some special applications. These are either experimental or numerical which are taken into account in this specified section.

The common application and hybrid systems are limited to building ventilation, hybrid with geothermal, hybrid with water desalination, hybrid with drying and a few works on hybrid with the fossil fuel systems. Therefore, it seems that many hybrid systems including photovoltaics with solar chimney, actual works for fossil fuel power plants, air filtration, extending the hybrid desalination systems, removing of the air pollutants of cities may be suggested for the future road map in this field and hybrid CHP systems may be introduced as the gaps which could have more potentials for the novel researches. Much more works are required for energy storage and generating electricity round the clock. Different types of PCMs should be utilized for a variety of chimney geometries. Also, CFD analyses are needed to be specified for the solar chimney hybrid systems. Table 10 shows a summary of the hybrid solar chimney systems and special applications.

Also, 36 references on the application works of the solar chimney were analyzed, and the applications were categorized into five parts including sea water desalination, drying, ventilation and passive systems for buildings, coupled with renewables and combined with Rankine cycle. The number of works done in each part of the application was counted, and the percentage of each part is presented in Fig. 43. According to the figure, ventilation and passive systems have the highest contributions in the applications of solar chimneys.

5. Geographical studies

In this section, we aim at presenting the works which have been carried out based on the potentials and the regions in the world. The most appropriate construction locations for solar chimney power plants are in vast desert areas where the land costs are so cheap. In this section, the papers in the field of studying the suitable area for SCPP constructions are reviewed. In 2003, Dai et al. [51] analyzed an SCPP in China. Three locations were selected in China in the Ning Xia Hui region as the pilot locations for constructing the solar power plants, because of its proper solar radiation characteristic in comparison to the other regions in China. They concluded that the solar chimney power plant with 500 m collector radius, 200 m chimney height, and 10 m chimney in the northwestern regions of China, was able to generate 110–190 kW electric power. Fig. 44 demonstrates that when the chimney height and collector diameter increase, the chimney power generation is increased nonlinearly.

Bilgen and Rheault [138] developed a mathematical model to analyze the performance of SCPPs at high latitudes in 2005. They evaluated the performance of SCPPs in a sloped land with 5 MW nominal power production for three locations in Canada, namely Ottawa, Winnipeg and Edmonton (Fig. 45). The Xinjiang region is the most proper area for installation of large solar chimney systems where the yearly insolation on the horizontal surface is over 1700 Kwh/m^2. The required land for SCPP of 100 GWh/year was up to 4 Km^2.

The middle latitude deserts of China that are named the Taklamakan have suitable climatic conditions and large areas of empty land. Papageorgiou [217] proposed that the middle latitude deserts of China are suitable for a large scale application of Floating Solar Chimney Technology. The feasibility study of SCPP as a clean energy resource for small islands of the countries in the Mediterranean region was analyzed for Split and Dubrovnik in Croatia, by Nizetic et al. [5] in 2008. The evaluation of the results was carried out by comparing the simulation of the proposed simplified model and the experimental results from the Manzanares prototype, which are shown in Fig. 46. Chergui et al. [218] presented a performance analysis of a solar chimney power plant located in the southwestern region of Algeria. Their results showed that the generated power by this system depended on the solar radiation, the ambient temperature, the height of the tower and the surface of the collector. The results showed that the insolation has more effect on the power generation than the ambient temperature.

The world's highest and largest plateau, the Qinghai-Tibet Plateau, is placed in the southwest China. The performance of the SCPP with salt lakes acting as heat storage system was analyzed by Zhou et al. [219] in Qinghai-Tibet in 2010. They demonstrated that the solar chimney power plant system in the plateau could generate much more power than the system constructed on the same latitude of other areas. In 2011, Hamdan [220] used a developed model to model and studied the possibility of SCPP for the United Arab Emirates climate. For forecasting the performance of SCPP, a simplified Bernoulli equation coupled with ideal gas and fluid statics equation was applied and solved using the EES solver. They reported that an SCPP with a collector roof diameter of 1000 m and chimney height of 500 m would generate a minimum power of 8 MW. A sloped 5 MW solar chimney power plant was designed to supply electric power to remote villages in northwest China, Lanzhou city by Cao et al. [221] in 2011. The designed plant had 252.2 m chimney height and 14 m radius. The angle of solar collector was 31° and the radius was 607.2 m. The overall efficiency of the power plant was low (Fig. 47).

Sangi [222] evaluated to performance of solar chimney at different locations of Iran. The optimum point of the performance was reported at 350 m chimney height and 1000 m collector diameter. The predicted power for this condition is 1-2 MW. In 2012, Asnaghi and Lajevardi [223] proposed to construct a solar chimney power plant in the central regions of Iran. For evaluating the SCPP performance and power generation throughout Iran, 12 different areas across the country were considered (Fig. 48). Iranshahr, Jahrom, Bam, Zabol, and Dashtestan have higher annual solar radiation comparing to the other selected regions. Zabol has higher average annual wind speed which may lead to increase heat loss from the roof of the collector. Ardabil possesses the poorest conditions with the lowest annual solar radiation and annual sunshine duration. The evaluation of SCPP performances in some regions of Iran has been studied previously. Asnaghi et al. [224] also analyzed the performance of SCPP to provide the off-grid electric power demand for the villages located in the Iranian central regions.

Cao F. et al. [225] reported a heat transfer model on a solar chimney. They evaluated the performance of SC in a conventional solar chimney power plant (CSCPP) and two sloped solar chimney power plants (SSCPPs). The main factors that influence the power generation at different latitudes of China are also analyzed. Mostafa et al. [226] expressed that Egypt has high solar radiation, high ambient temperature, and large desert, so the country is appropriate for installation of SCPP. Ali et al. [227] developed a simple mathematical model to analyze the performance of a power plant for electricity generation in Baghdad city of Iraq. The model was validated using the experimental data of the Manzanares prototype. They found that the output power is effectively dependent on the chimney’s height; it yields moderate increasing in power output when the height is increased from 195 m to 300 m. Also, the chimney's diameter has a lower impact on the solar tower output power in comparison with the other dimensions of the solar tower when it increases from 10 m to 20 m. Gholamalizadeh and Mansouri [27] developed analytical and numerical models to forecast the performance of an SCPP in Kerman, Iran. They presented a new approach for evaluating the effect of the site altitude on the possibility of SCPP and thus a coefficient named "the altitude effectiveness" was identified using the geometrical parameters of the Manzanares prototype in various site altitudes. The altitude effectiveness is defined by Eq. (2):

$$\varepsilon = 1 - 2.705 \times 10^{-5} S \quad (2)$$

Where S is the site altitude in m. Fig. 49 illustrates the altitude effectiveness and the effect of the site altitude variation on the power output for solar insolation of 1000 wlm^2. For instance, as shown in Fig. 49, the generated power of the plant in the altitude of 3600 m (e.g. La Paz, Bolivia), is about 9.7% less than the power output at the mean sea level.

The DESERTEC project proposes the construction of a high-voltage direct current (HVDC) electric grid, connecting Europe with the MENA area. Through the HVDC grid, solar electricity can be generated in MENA area and sent out to Europe. This SCPP can produce electricity more than 80 GWh per year. The cost of this SCPP construction will not be more than 40-48 million Euro [228]. Ratanachotinun and Pairojin [229] studied the possibility of using glass solar chimney walls (GSCW) in Bangkok, Thailand. The GSCW is usable in office buildings or mini-buildings in the tropical climates to maintain energy and the environment. Attiq et al. [230] investigated a 3D CFD model of a solar chimney power plant and compared it with the prototype of the Manzanares plant to study the SCPP operation in Tunisia. Akhtar and Rao [231] studied the economic efficiency of SCPP for 200 MW capacities, in Rajasthan India. Depend on the capital cost and the operation cost, the maintenance and the levelized electricity costs for SCPP were estimated and compared with the other power plants.

A feasibility of solar chimney power plants in North Cyprus was studied by Okoye and Atikol [232]. Cost analysis was developed to find the most feasible cost choice for installing solar chimney power plant. In 2014, the annual performance of solar chimney power plant was analyzed by Guo et al. [233] in Sinkiang, China. The influences of chimney and collector radius on the power output were studied. They reported an obvious seasonal variation in the power generation of SCPP. A comparison of three technologies including solar chimney, CSP tower and PV farm was carried out by Bayeh and Moubayed [234] in Lebanon to find the best way to producing electricity.

Gaps in the geographical studies: More comparison studies in different altitude and longitudes in the world between several areas in a region or between several cities or countries in a continent are required. Also, geographical studies for different applications such as drying, desalination and ventilation are the situations, which have been less paid attention. Also, decision making techniques for the regions for the purpose of installing solar chimney power plants shall be taken into account with the GIS technique for the purpose of identifying the potentials. A summary of the literature is demonstrated in Table 11.

6. Conclusion and suggestions for future works

In this study, a comprehensive literature review is conducgted based on over 200 studies over the past 30 years on solar chimney systems. The results of most work are briefly reported to show a general concept of each work. The results show that just around 20% of all the studies have been done experimentally. Lacking of reliable experimental validation stands as a major hurdle for both theoretical or modeling studies. It was noted that most of the solar chimneys have been built and installed in small sizes, which are not economically beneficial, and the need for building large-scale solar chimney is clear t. For high reliance on the private sectors, it is suggested to develop chain projects from feasibility, simulation and small-scale, then scale up to the large-scale solar chimneys.

In the aspect of application types, 36 applied papers were investigated. The result shows that the most applications are allocated to the following five cases: building ventilation and passive systems, combined with renewables, sea water desalination, drying and combined with Rankine cycle: whereas their contributions are 32%, 29%, 21%, 12% and 6%, respectively. It shows that there are many blank areas for other applications and investigations. According to what was analyzed in the gap study, the following suggestions could be proposed for future studies:

- Building large and updated power plants are highly suggested to have more reliable references for theoretical and modeling studies.
- Converting the simple systems to hybrid, obtaining the optimum dimensional harmony between the chimney and collector dimensions, comparing different sizes and optimizing the systems optically are recommended.
- Performing experimental works on solar chimneys with the turbine and focusing more on the turbine elements, structure and performance.
- Working on other applications of solar chimney such as air filtration and CHP systems.
- Much more works on energy storage and generating electricity in solar chimneys.
- Exergy and exergo-economic analyses of solar chimney.
- Simulation of hybrid solar chimney power plants with other renewable energy systems and fossil fuels power plants is another subject that has the situation for more works.
- The decision-making methodologies are suggested for future installation of solar chimney power plants

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