Innovative Progress in Solar Chimney Power Plant Efficiency Improvements: A Comprehensive Review

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Abstract

Utilizing solar chimney power plants (SCPPs) for manufacturing clean and environment-friendly energy has drawn a lot of attention and has (over the passing decades) become one of the most promising solutions in the solar energy field . Low efficiency, construction difficulties and other required improvements have encouraged researchers to work on this system. Many researchers put their efforts into proposing an optimized configuration for the main components, whereas others have proposed innovative ideas and add-on accessories to improve solar chimney power plants from an efficiency or construction viewpoint. This paper provides a comprehensive review of the past few decades, and includes theoretical, experimental and numerical studies focused on optimizing the main characters of the system such as the chimney, collector and power conversion unit (PCU) together with other recently suggested innovative ideas and alternative technologies to improve solar chimney power plants efficiency. Concurrently, other researchers focused on hybrid solar chimney power plants to produce desired by-product such as distilled water and so make SCPPs more practical.

Highlights

- Different types of solar chimney power plant systems are reviewed in this paper
- Various techniques toward system improvement have been categorized and discussed
- Developments in hybrid solar chimney power plant systems are reviewed
- Experimental, numerical and theoretical studies are summarized and main effective results are pinpointed
- Key important innovative ideas and strategies for improving basic components are studied alongside integrated apparatus inserting layouts

Keywords: Solar Chimney Power Plant; Renewable Energy; Solar Collector; Hybrid Solar Chimney; Accessories and Alternative Technologies.

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1. **Introduction**

At this time, what with the noticeable growth in energy consumption all over the world, the limitations of energy resources, the environmental problems of fossil fuels energy and the hazards of climate change, choosing a clean, reachable and abundant energy resource are becoming a vital necessity [1, 2]. Population growth and increasing living standards are causing an ever faster-growing energy demand. Added to which, fossil fuel depletion and Green House Gases (GHG) pollution are becoming, more than ever, a burden on the environment. Furthermore, this shortage of current energy resources and the global warming concerns has forced governments and decision-makers to effect a change to renewable and sustainable energy resources. Hence, in the last few decades, designing a sustainable and efficient system to produce power has, more than ever before, become an essential research issue because access to a free and durable source of energy is necessary for progress[3]. Considering all energy resources – fossil fuels, nuclear energy, geothermal, hydro, biomass, solar energy and other types of resources, almost all of them have some detrimental effects on the environment, but solar energy is more available, durable, has limitless energy potential, and more importantly, has causes minimal damage to the environment. In this respect, solar chimney power plant systems (SCPPs) use solar radiation for power generation and consist of three basic components: a collector – generally a huge circular and transparent roof [4], a chimney or tower –a super-tall tube, and a power conversion unit containing a turbine to convert kinetic energy into electricity. The chimney is installed in the center of the air collector and utilises the buoyancy effect so warm air rising through the chimney once the air temperature within the 'greenhouse effect' collector has risen sufficiently [5] operates the turbine, as shown in Fig. 1.

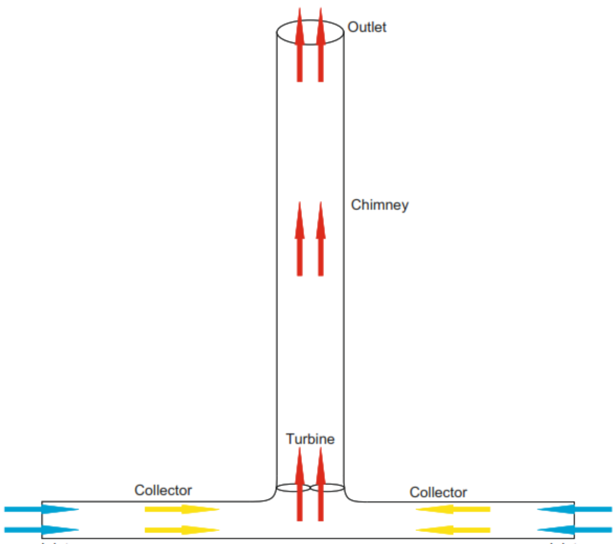

Fig. 1. Solar chimney power plant (SCPP) schematic

Multiple energy conversions take place in this form of power plant, converting from the thermal energy of the sun into kinetic energy of flowing air and finally into electricity. Despite the simplicity of the principle, several issues exist, the foremost being their low efficiency [5]. In addition, there is the problem of the intermittency (inherent of such energy sources) on rainy or cloudy days [6]. Notwithstanding, many obstacles have been overcome at some level with the application of new concepts, nonetheless, there is still room for improvement – which has kept this topic as a center for research attention. With lower construction and maintenance costs, simpler technologies, cheap materials and little (if no) need for a high specialist input (particularly full time), this energy system have become an interesting technology for many countries [5] – particularly in remote areas and desert climates with their high solar irradiances and no translation losses.

There have also been numerous published works on SCPPs due to its capability for industrial and urban applications including reviews, and numerical and experimental studies [1, 7-21]. Nonetheless, this present review introduces a more detailed, updated and comprehensive information approach related to the modern developments in this technology. An applicable and innovative study including both experimental and analytical studies is presented in this work to cover all the recent studies performed on enhancing the efficiency of SCPP, necessary because innovation plays a pivotal role in their progress.

Moreover, because of their low efficiency, researchers have compensated for this by coupling the SCPPs with other units, which then results in hybrid plant capable of the desalination of water; generation of power; drying products; heating and ventilation and etc. Hence, because in recent years the integration of SCPPs with other units has become a focus of attention, this review also considers hybrid SCPPs to identify other gaps for future studies.

1.1 Renewable Energy and the Environment

The high rate of population growth coupled with a remarkable growth in developments and lifestyle standards, has resulted in a rapidly increasing global energy and water demand during the last couple of decades, as shown in the Fig. 2 [22]. Coupled with this is the problem that, currently, fossil fuels are the world's dominant fuel source and it is this proportion of usage (compared to other resources), which leads to excessive GHG emissions. These, in turn, exert several profound, but negative influences on the environment which promote regrettable Worldwide changes, such as receding glaciers, earlier plant blooming, ocean acidifications, killer heat waves, even butterfies retreating up mountainsides [23]. Notwithstanding, all nations will encounter precipitation shifts that may vary from region to region [23].Therefore, in order to help control these impacts, will require utilizing alternative choices for our energy resources, such as renewable energy resources, which noticeably reduce some of the detrimental effects of GHG emissions [23, 24].

Fig. 2 represents the world energy consumption in 2019 in million tones oil equivalent (MTOE). World energy consumption increased by about 3% in 2018. Gas had the largest increase, followed by renewable energy [22]. From the same figure also shows that oil remains the world's leading fuel, making up a third of the total consumption. In 2009, all of the fuels, except oil, fell moderately. Renewable energy consumption experienced a gradual increase.

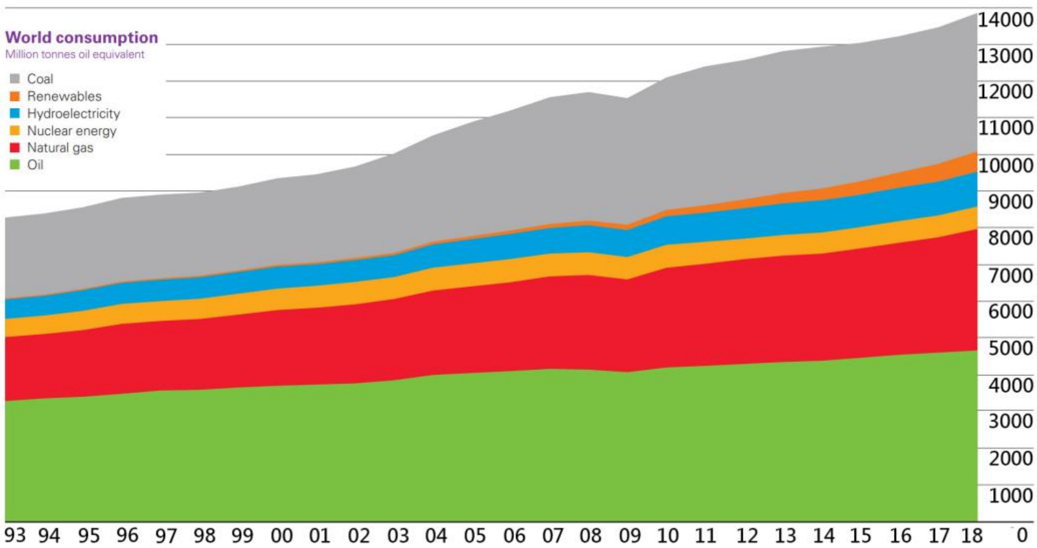

Fig. 2. World consumption in Million tones oil equivalent[22]

1.2 Solar Energy and Solar Chimney

It has been claimed that solar power could be used to reverse the damage being done by other environmentally-damaging energy production methods [24]. It is one of the most promising renewable energy resources, it is both clean and safe [24], and amongst all of solar power technologies (depicted in Fig. 3), PV cells play a great role within the market to supply power demands. However, they are still exhibit low efficiency, high-temperature drop-off, and are vulnerability to harsh winds. All of which remain a problematic issue. In addition, concentrating solar power plants are strictly dependent on direct solar irradiance, something that SCPPs can turn to their advantage, because they do not depend on just radiation that coming from the direction of the sun. Another further problem of solar energy power production devices is their intermittency, but this difficulty could be handled to some extent in SCPP systems by utilizing a capability to harvest thermal energy stored in the ground and so produce a limited amount of power even at night. Something not seen in the other types of solar power plant. To improve this ability, some researchers have also suggested exploiting phase change materials (PCM) – (like paraffin [25, 26] and Glauber's salt (Sodium Sulfate Decahydrate) [27] – as a latent heat energy storage medium to store more energy for nighttime power generation. Sedighi et al. [28]investigated the effect of PCM porosity on the SCPP performance numerically. On the other hand, Fadaei et al. [29] used an artificial neural network to investigate the performance of SCPP, and Rafea et al. [27] ran an experimental setup to investigate the effect of PCM material in

SCPP performance enhancement. Even so, simpler and cheaper concepts, like filled water tubes [30], could still enhance sustained power generation utilizing the earth surface soil's ability to act as a power storage device for a system.

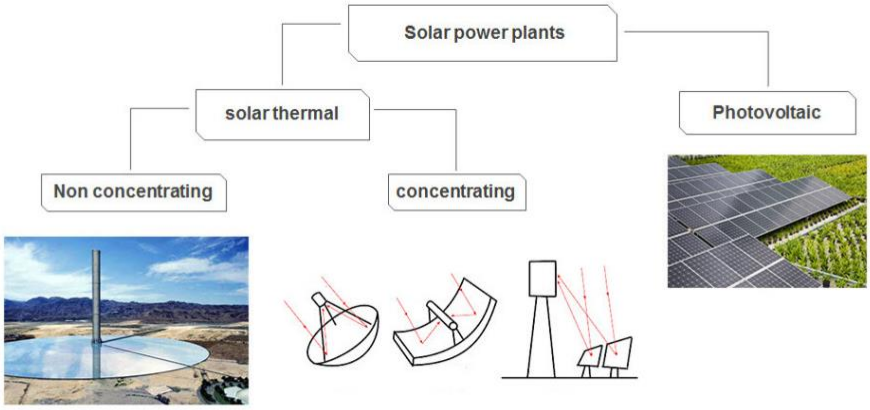

Fig. 3. Types of the solar power plant based on the working mechanism

The SCPP is a large-scale power generation unit which absorbs solar radiation and converts it into the power through the installed equipment [24, 31-33]. The multiple energy conversions taking place in SCPP are: solar radiation to thermal energy, thermal energy to kinetic energy, kinetic energy to mechanical energy, and mechanical energy to power, respectively [1].

The first chimney power plant was proposed by Cabanyes [34] in order to heat a house and generate electricity through an installed wind propeller, although the basic idea was not a new innovation as many years ago, Leonardo da Vinci designed a barbecue which worked using the basic idea of the updraught within a chimney [35]. However, the first actual prototype was constructed by Schlaich et al. [5] in Manzanares, Spain in 1982 as shown in Fig. 4. Their objective was to determine the efficiency of the system [36]. The height of the constructed prototype is 194 meters and collector diameter, tower diameter and collector inlet heights are 244, 10 and 1.8 meters, respectively. The total weight of the prototype is approximately 125 tons. Construction of the Manzanares power plant was an inspiration to start innovative researchers in other countries to study the feasibility, in places such as China [12, 15, 37, 38], Iran [39, 40], Mediterranean region [41], Algeria [42, 43] and other countries.

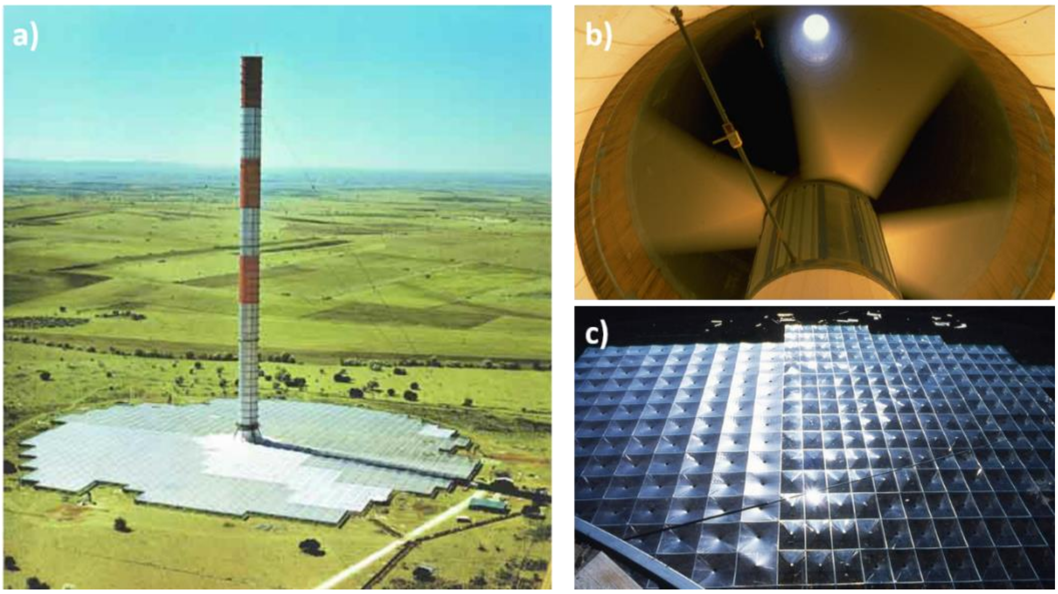

Fig. 4. Different sections of the solar chimney in Manzanares, Spain; a) side view of the SCPP, b) Turbine, c) Collector[44]

2. Basic Components of the Solar Chimney Power Plants

The SCPP (solar chimney power plant) is a system that converts both direct and non-direct irradiance into a clean reliable and environment-friendly power. This eco-friendly system is composed of a collector – that plays a role in absorbing irradiance and heating air by the greenhouse effect phenomenon, a large chimney – that plays an important part in conducting heated air through the turbine and atmosphere and a turbine as the final power conversion unit, as illustrated in Fig. 5. From these beginnings, there has been considerable focus on how to optimize the main components of SCPPs in order to harvest more efficient power.

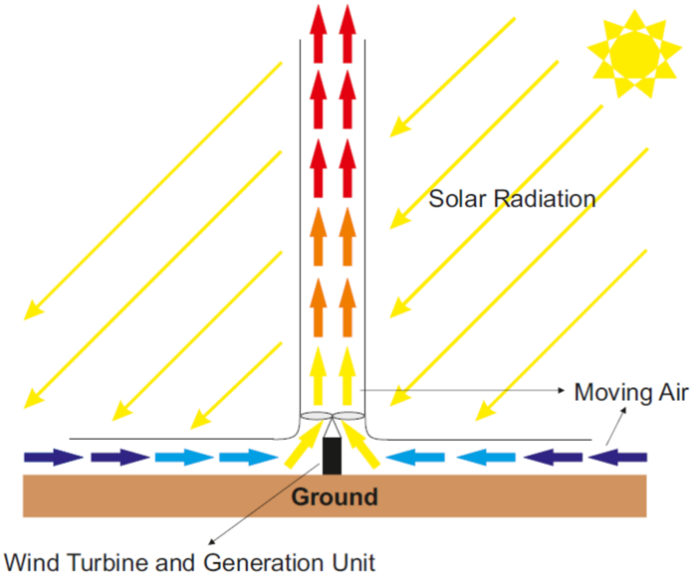

Fig. 5. Mechanism of solar chimney power generation

Many researchers have put a great effort into this area, exploiting experimental setups, theoretical models and numerical simulations to understand the mechanism and present an optimum amount of basic parameters such as: chimney height [45], chimney diameter [46], the divergence angle of the chimney [47], the ratio of height and diameter in the chimney[48], collector radius and collector inlet height [46, 48, 49], all of which have been considered as the most relevant parameters that influences a SCPP's performance. As a simple precept, Schlaich et al [50] stated that solar tower power output is proportional to the size of an imaginary cylinder that encircles the chimney inlet area and extends to the height of the chimney. However, although early studies reported that power output is directly proportional to collector area and chimney height, finding an optimum value for each parameter and the best configuration for a solar chimney remained as an argument for discussion, and there was not a complete investigation that included all the parameters. Additionally, limitations from a practical viewpoint of regional dependences and economic considerations should be considered before proposing an optimal efficient SCPP design.

2.1 Chimney

The part of the system that conducts heated air from the collector part to the atmosphere, utilizing the buoyancy effect causing by inside and outside of apparatus temperature differences has been called a 'chimney', 'updraft tower' 'or a solar tower'. Irrespective of the term, it is a gigantic tube that is sited at the center of the collector acting as the thermal engine for the plant. Despite the long tube, it has been claimed that the chimney has a low friction loss because of its suitable surface to volume ratios and so likened to a hydropower station pressure tube or penstock [50]. Chimney efficiency is given by the following equation and depends on height in a particular case [24].

$$\eta_{chimney} = \frac{g.H}{c_p.T_0}$$

Using the Boussinesq approximations, the speed reached by free convection could be calculated. Indeed, for a chimney with a height of about 1km, deviation from the exact solution given by the Boussinesq approximation is negligible and the error is trivial [51].

Even though it is reported that the output power grows with the square of the chimney height [46] as a result of the increased mass flow rate, approval for a large chimney height are not always available so this claim has yet to be fully verified. In addition, there are still constructional limitations, and other natural hazards are inevitable when making such a large chimney. Moreover, aero thermal characteristics of flow, inside and over different chimney shapes, could strongly affect power output. Backflow concerns should also be considered.

Nonetheless, many configurations have been proposed to cope with this issue, although a large chimney is still vulnerable to a harsh wind storm and other natural forces like seismic activities [52] especially with super-tall chimneys and for non-urban areas which have a greater interest in their operation [53-55]. Wang and Fan summarized 739 types of high chimneys failure cases and compared effective factors in observed failures in a complete review [56].

Schlaich [57] considered the danger of buckling as the reason for the height limitation of natural draught cooling towers which was about 200 m. He suggested stiffening spoked wheels as a countermeasure.

Many layouts have been proposed in respect of structural choices to deal with possible structural failure, but the best choices of material still proved to be reinforcement concrete, guyed tubes made from corrugated metal sheet, and cable-net designs with cladding or membranes which is an appropriate choice for less developed countries [50, 58, 59]. Constructional consideration for the chimney wall thickness would suggest decreasing wall thickness from about 1 m just above the support on radial walls to 30 cm halfway up, which then remaining constant all the way to the top, stiffen at several levels with cables arranged like spoked wheels within the tower to counteract over-toppling caused by wind suction in flanks and the use of these thinner walls [59]. Structural configurations are illustrated in Fig. 6.

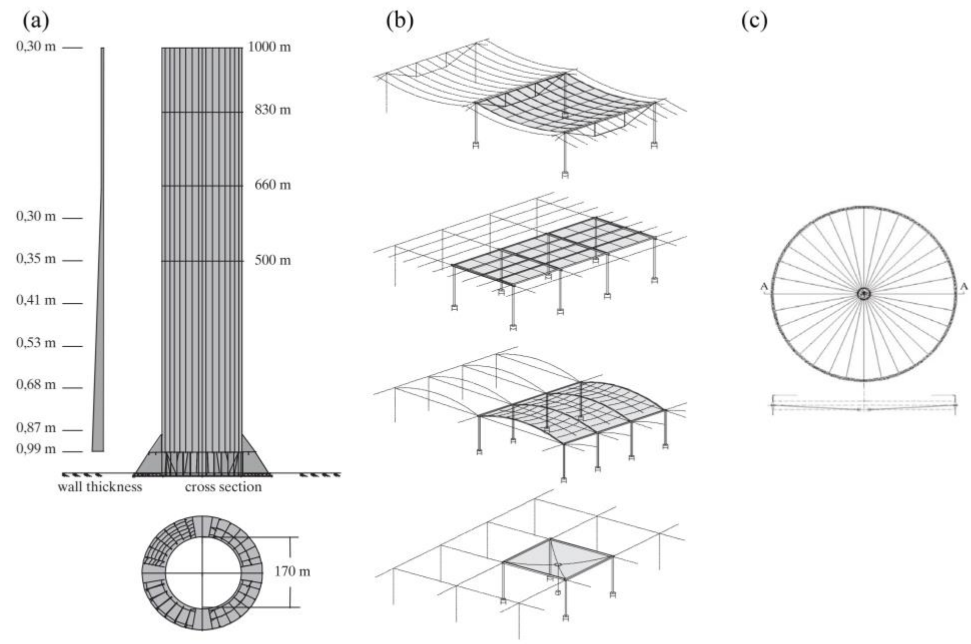

Fig. 6.Structural configurations:(a)Wall thickness variation of a 1000 m height and 170 m diameter tower;(b)Collector design options; and(c)Spoked wheels, the spokes are made of vertical steel slats [59]

However, a limiting factor in an increased chimney height is the fall in rising air temperature due to heat loss and its decreased velocity due to flow loss, with subsequent reduction in buoyancy. Accordingly, the greater flow loss and lower buoyancy effects with higher chimneys limits chimney height for optimized power output. Demonstrated by Zhou et al [45] for the first time, they emphasized that there is a maximum height for the chimney, and this that increases with the collector radius. To overcome this limitation researchers then started looking at optimising other parameters [60]. For example, it was shown that an increase in the collector area could compensate for a lack of chimney height [50]. Cottam et al. [46] suggested a linear relationship between power output and collector radius the same as the chimney radius. Schlaich [57] claimed the same output may result from a large chimney with a small collector roof area and vice versa – although this is not strictly a linear correlation (between power output and collector area times tower height) because of collector friction losses [50] – and he also implied there is no optimum physical size for solar Chimneys. Additionally, to decide the optimum dimensions the specific construction costs of each item must be known.

From a building cost viewpoint, Wolfgang Schielcl suggested that operating a large chimney is much cheaper than operating many small ones [58] even though Cottam [46] prefer several smaller collector with the size of 3000m over a very large one. More recently, other investigations to cope with chimney difficulties have been undertaken but the discussion still continues. For example, to evaluate the effect of diameter, a chimney 'slenderness' ratio parameter has been defined which is the ratio of chimney height to chimney diameter. Normally slenderness ratio could vary from 5 to 12 influenced by various reasons. However, Petrorius [61] reported an optimal slenderness of 5-6, considering the risk of cold air inflow. There is also a critical value of 6-8 and it is claimed that the diameter has a prominent effect under this value [62]. Considering the influence of winds, Kashiwa [56] suggested the slenderness ratio of 12 and mentioned that wind variation could have a great influence in the updraft.

2.2 Collector

One of the major parts of the SCPP, the collector plays the role of a heat exchanger within the system, in that the collector converts solar radiation into thermal energy utilizing the greenhouse effect. The thermal energy of a heat absorber first warms the air and then the thermal energy of this heated air is converted to kinetic energy due to its buoyancy effect. A transparent roof, column structure and support matrix are all major parts of the collector, and the principal mechanism occurs when irradiance through the transparent canopy hits the absorber section. The transparent canopy, which is often plastic or glass, is then not able to pass any infrared radiation emitted from the absorber back to atmosphere, but instead the absorber heats air which is then exploited by the overall process. Although, as has been mentioned, that output power is directly proportional to the collector radius, similar to chimney height, the collector area is limited. Guo et al reported a maximum collector area for the Spanish prototype through a MATLAB program [49]. Collector inlet height, collector inclined angle and collector profile shape are the major parameters of this study. Despite great effort from many researchers, the issues governing an optimal collector taking in to account all parameters, remains, at this time, still unsolved – the same as with the chimney. Because optimal dimensions must include economic factors, many researchers have pragmatically employed a multi-objective optimization approach [63, 64], from which various researchers have proposed alternative ideas to improve collector efficiency and for harvesting more power.

2.3 **PCU**

Finally, the Power conversion unit (PCU) consists of one (or more) turbo-generator(s) (turbine coupled with generator), the output from which depends on the air mass flow rate being fed to it from a horizontal to vertical transition section (HTVTS) between the collector and the chimney. With some designs, inlet vanes have been used to redirect and guide the flow through the turbine, but the PCU may also include a diffuser located behind the turbine for the single turbine configuration. Bernardes et al. [65] presented a series of possible configurations for the HTVTS based on three basic geometric configurations which are given in Fig. 7, simulating thermodynamic behavior using natural laminar convection. The concern in the power conversion unit being the recirculation of air flow caused by unsuitable configuration choices. Bernardes et al. stated that mass flow rates for rising air are greater for a conic SCPP, and Yan et al. [30] considered that straight junctions induced the lowest mass flows due to flow recirculation. Later Muller [66] found a 43 percent loss reduction in multiple horizontal axes with guiding cones.

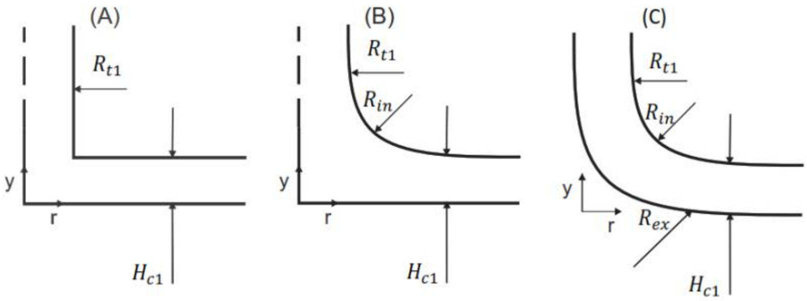

Fig. 7.Structural configurations of horizontal to vertical transition section (HTVTS) [65].

With regards to the siting of the turbine, some layouts have been proposed. Pasumarthi and Sherif [14] suggested installation at the top of SCPP whereas in most literature, turbines are located in the base because of installation and maintenance difficulties, especially for super large SCPPs. Bonelle [23] observed a relatively negative pressure in SC for in-base installation and relatively positive pressure for in-top installation, explained by the fact that static pressure must drop from upstream to downstream. Further, many arrangements have been proposed for the actual turbine configuration – a single vertical axis, multiple vertical axes and multiple horizontal axes that could contain inlet guide vanes (IGVs) or not (all as shown in Fig. 8). Schwarz and Knauss [67] designed a single vertical axis for SC and Gannon and von Backstrom [68] utilized supporting structures for IGVs. Bilgen [69] suggested one pair of counter-rotating rotors as an alternative turbine layout. In fact, the proper choice depends on the solar chimney size. In small solar chimneys, multiple turbines may not be a good selection, whereas for super large systems this could reduce manufacturing costs and maintenance challenges. In the power conversion unit junction, the shape of the collector into the chimney also has a significant effect on the thermo-hydrodynamic field quality. Chergui et al. [70] investigated different junction shapes and their resultant junction with the diffuser had a higher mass flow rate in comparision to the curved junction and the straight junction.

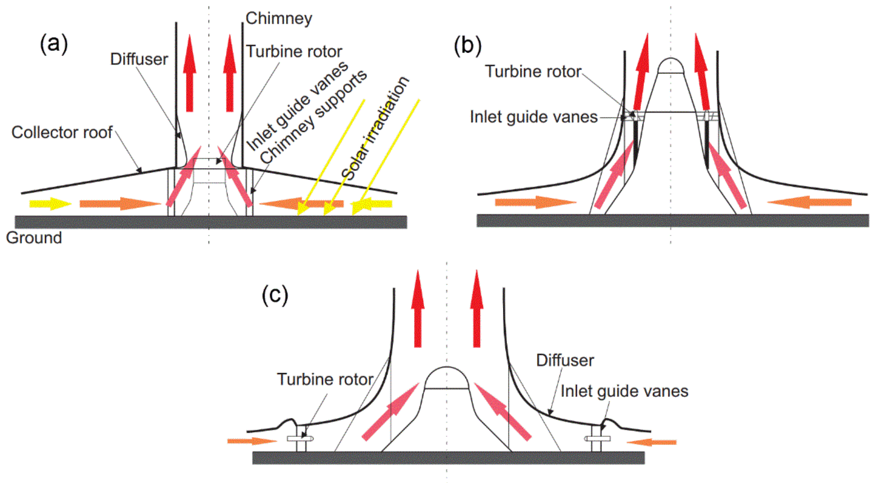

Fig. 8. Configuration of turbine installation: (a) single vertical axis; (b)multiple vertical axis and; (c)multiple horizontal axis[1]

Ayadi et al. [71, 72] investigated the effect of turbine diameter and the number of blades and reported that turbines with the largest diameter and the lowest number of blades are the best option for small scale SCPPs. Kasaeian [73] conducted a 3D simulation of large scale SCPP considering turbine blades. However, contrary to Ayadi's experimental setup, Kasaeian reported that a turbine with 5 blades, presents more power output than that with 3 blades, whilst 3-bladed turbines provided a higher mass flow rate. More research is needed in this subject to determine an optimal turbine configuration.

3. Innovative Ideas and Alternative Strategies

Despite the clean and eco-friendly energy production from SCPP systems, their disadvantages of noticeably low efficiency and high construction costs are considerable. To reduce these problems, researchers have focused on finding the optimum configuration and alternative choices to improve SCPPs efficiency. Optimizing major parameters, studying different configurations, utilizing different mechanisms such as thermal fins or accessories like intensifiers, and combining these with alternative systems such as water desalination – have been widely studied with a view to improving system power output and providing a reasonably efficient economic system.

3.1 Different Geometry Configuration

To deal with low efficiency the first and simplest option is to optimize the major components and make changes in their basic configuration. This is simple and incurs lower costs in comparison to integrating systems or involving different accessories. Numerous researchers have focused on applying different configurations and optimizing related parameters in an effort to improve SCPP efficiency.

3.1.1 **Chimney**

One focus has been an investigation of different chimney configurations, and these include changing the cylindrical shape of the chimney or presenting novel layouts. Ming et al. [74] studied the effect of divergent and convergent chimney angle and chimney height to allow a better understanding of different shape parameters. They compared results obtained against a reference case including a cylindrical chimney shape. With the divergent type of chimney, the diameter increases slightly with height, and this affects the low static pressure at the chimney inlet and consequently has a significant effect on the air velocity value which promotes greater airflow inside the system. Okada [75] et al. suggested a diffuser type chimney to increase the power generation in the system. The result of their CFD analysis in large scale plants revealed that a focused airflow in the throat increased power generation and the flow speed throughout the chimney, but especially at the bottom – a precept which was further studied on an indoor scale solar chimney. They concluded that a divergence angle of 4 degrees increased the power output by about 3 times that of a straight chimney. Jameei et al. [76] assessed 15 types of chimney walls based on a three-step procedure from convergent-divergent form to circular concave-convex and parabolic curve. The results showed about a 50 percent increase in velocity for the parabolic curve. Koonsrisuk et al. [77] investigated both the effects of collector slope and chimney convergence and divergence angle. Patel et al. [78] also performed a series of twelve case studies to investigate the effect of chimney divergent angle and collector height. Ohya [79] et al performed an indoor laboratory experiment analysis and showed power output for diffuser-type towers can be increased by 4 to 5 times in comparison to conventional towers, but also showed a dependence on air temperature increments inside the collector. Nasraoui et al. [80] found that the chimney divergence angle has an optimum value depending on chimney height. Their findings revealed that the optimum divergence angle to solar chimney scale relationship is nonlinear, and that the value of the divergence angle decreases by increasing the solar scale and hence for commercial SCPPs the optimum divergence angle would be the more suitable choice.

Hu et al. (Fig. 9 [81]) carried out several case simulations to discover the best shape for the diffuser type chimneys, and they reported that diffuser type chimneys could handle more than 13 times the power output than simple cylindrical solar chimneys. They showed different parameters of AR (area ratio) and H_d/R_{in} (where H_d is divergent section and R_{in} is the start of the divergent section) could affect the aerodynamic characteristics of flow inside the chimney and expansion loss, both of which directly affected performance. Comparing simulation results revealed that a divergent solar chimney configuration which has the largest H_d/R_{in} is best option for power generation, DISC is second-best option and DOSC is the last. Hu proposed a controlling approach for the design of a solar chimney containing a variable diffuser outlet. The concept being that the user could change the area of the outlet and so adjust the fluctuating power output.

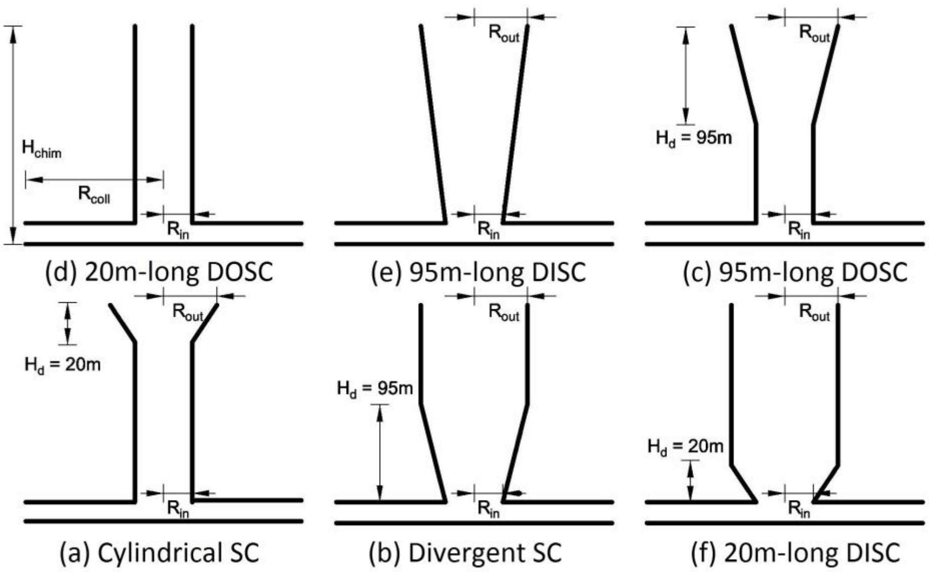

Fig. 9.Examination of three different diffuser type carried out by Hu[81].

Hu et al. [82] studied a wide range of AR changes of the tower from 1 to 32 and emphasized that power output improvement is dependent on chimney height. However, the situation is not that simple. Divergent chimneys can act like a diffuser, and this has a concerning impact on flow characteristics. Formation of large eddies near the wall in a diffuser represents the onset of stall phenomena, which could then lead to flow blockage and unwanted backflow. In the Xu Zhouet al. [83] investigation, with small outlet to inlet AR cases, flow goes up normally without any backflow, but the stall phenomena was observed for outlet to inlet ARs larger than 11.9. For even larger divergence angles, backflow occurs over a larger proportion of the flow area and boundary layer separation occurs lower down within the chimney. This backflow brings ambient air into the chimney, which then reduces the average temperature and leads to a large reduction in buoyancy and pressure potential. Further chimney configurations, such as convergent chimneys and opposing (convergent-divergent chimney) designs have examined by Bouabidi et al. [84]. Their results showed that the air velocity values are affected differently by each configuration. For example, the divergent chimney revealed the best results in this study, whereas the convergent configuration degraded maximum velocity, and opposing chimney only enhanced the velocity compared to the standard case. Chimney divergence and convergence investigations are summarized in Table 1.

Table 1. Chimney divergence and convergence investigations

Investigated divergence and convergence angle[†](DA), (CA) and area ratio (AR)	Optimal range	Chimney height(m)	Power output[‡] equalized by the power of reference case (AR=1 OR DA=0)	ref
AR (div):1.56,2.25 AR (con):0.25,0.56	-	800	AR (div):1.06,1.07 AR (con):0.8,0.95	Ming[74]
AR (div):1,2,4,8,16,32 AR (con):0.25,0.5,0.75	AR (div):16	100	AR (div):1,4.27,18.49,69.07, 179.16,120 AR (con):0.02,0.09,0.19	Koonsrisuk et al.[77]
DA:1,2,3	2	10	7,10,9.8	Patel et al.[78]
AR (div):3.09,12.39,49.56	12.39	10	7.9,13.6,11.2W (absolute power)	Vieira et al.[85]
DA:4	-	0.4	3	Okada[75]
DA:2.4,4,7 CA:4,7	DA:2.4	-	DA:4.2,3.9,2.8 CA:0.8,0.4	Chergui[70]
DA:0,2,4 and 6	4	2	11.8,31.93,52.5, 46.74 mW.(absolute power)	Ohyaet al.[79]
AR (div):1,4,10,22,32	10	200	1,8.5,13.5,10,6.6	Hu et al.[82]
AR (div):3.94,8.76,11.83	8.76	194.6	7.58,11.9,7.2	Xu et al.[83]
DA:0,1,2,3	1	195	34,70,64,49 kw (absolute power)	Aakash Hassan et al.[86]
AR (div):4,6,8,10,12	10	195	440,604,678,702,695kw (absolute power)	Hu et al.[81]
AR (div):4,9,16,25,36 AR (con):0.25	AR (div):16	12.3	AR (div):15.3,24.3,26.1,19.5 ,15.3 AR (con):0.2	Lebbi et al.[87]
DA:2,3,6,9	3	100	66,69.3,61,44.5	Nasraouiet al.[80]
DA:1,2,3,4,5	2	7	0.63,1.07,1.04,0.95,0.86 (W power)	Pritam et al.[88]

Further researchers have investigated different practical configurations for the updraft tower manipulating the chimney profile. Nasraoui et al.[89, 90] proposed a hyperbolic-shaped profile for the chimney and the results suggested an enhanced

[†] degree
[‡] The extracted values from diagrams and tables and in case of velocity report values obtained from turbine model power output $P = 0.5.\rho.A.u^3$

power output in most cases. As before, the power rise suggests an optimum range, but these are more effective for larger outlet to inlet diameter ratios, showing almost constant chimney efficiency changes with very large diameter ratio, whilst with the conical section, degradation was higher in large values. In comparison against conventional conical chimneys, the hyperbolic chimney showed a 45 percent enhancement with a diameter ratio of 8. This comes because a conical chimney increases power by 250 percent compared with a straight chimney with the same diameter ratio. The conclusion is that a diverging chimney, with different shapes might then form a key parameter in enhancing the performance of SCPPs and so present an attractive solution for low-efficiency SCPPs.

A further idea of utilizing air flowing into a low static region was suggested by Okada et al.[75, 91]. They suggested utilizing a 'brim' that acts as a vortex generator and so provides a low-pressure region in the chimney outlet, and this idea, exploited in the wind-lens, has resulted in a two - threefold increase in power output [92].

3.1.2 Collector

The collector is the second major component of a SCPPs and has a significant effect on the performance of the system. Early researchers have therefore investigated the impact of the major collector parameters in order to better understand the effect of these [93]. And whilst the dimensions of the collector radius and the chimney height are considered factors directly affecting power output, many investigations have suggested that collector radius could have a greater significance on performance and consequently, any increase in chimney size is more effective with large diameter collectors [94, 95]. Ming et al. [74] studied the effect of collector height in addition to the collector radius, to better understand the different shape parameters, and although decreasing the collector height led to an increased power output, collector height showed of less importance compared to the other major parameters such as chimney height, collector radius and chimney diameter [85, 94]. Sandeep et al. [78] stated there is an optimum value for the inlet opening height and that, in fact, a very low of inlet opening height could end up reducing the power output because of a lower mass flow rate. Flat collectors cause pressure drop due to a cross-sectional restriction of flow near the chimney, but sloped collectors are a promising solution. Hence the slope of the collector could play an important role related to the quality of hydrodynamic flow inside the chimney, the same as chimney divergence and convergence angle as discussed earlier (Fig. 10). Hakim Semai et al.[96] reported an entropy reduction in converging SCPP. Sun et al. [97] also investigated the effect of inclined angle vs. power output and other flow characteristics for the collector. They observed vortices appearing and increasing inside the collector, especially near the chimney position, with positive inclination angles (β). Aakash [86] and Ayadi [98] also studied the effect of the collector slope, and reported that a negative inclination angle leads to a higher velocity and hence a higher power output as a result. Ayadi suggested a 125 percent increase in velocity for a variation of 2.5 degrees in inclination angle. Aakash also suggested that increasing the inclination angle could result in a higher mass flow rate and larger air velocity. Although very large angles – about 6 degrees – could lead to air recirculation within the collector due to a density gradient and hence cause air blocking as a result.

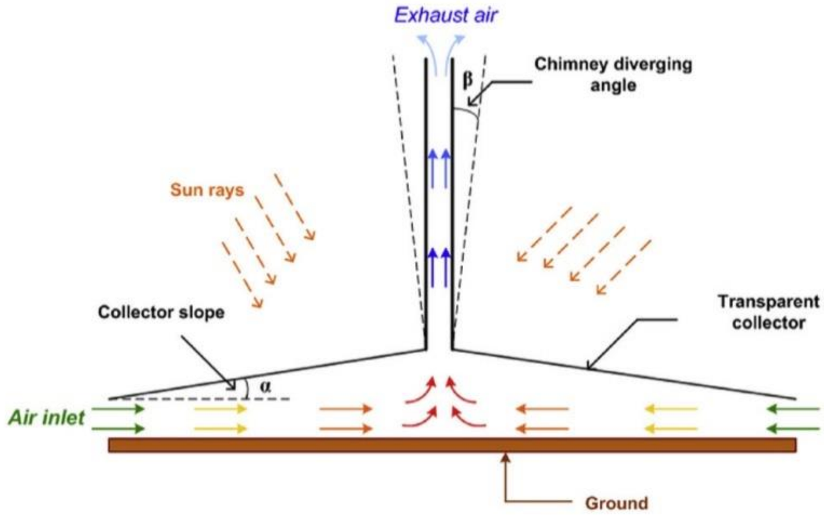

Fig. 10. Chimney diverging angle α and collector inclined angle β[86]

Sandeep et al. [78] investigated the influence of both collector outlet height and collector outlet diameter. Their results for the collector output height correlates well with other investigations and indicates that a large collector output height could limit growth in power output. They also observed a strong effect regarding the collector outlet diameter and claimed that with a large value of collector outlet diameter, a larger quantity of air is able to enter the chimney with a reduced flow resistance producing greater power. Kebabsa et al. [99] investigated different collector entrance configuration parameters, including sloping distance and angle. They proposed even better result in comparison to normally inclined collectors, with up to 13 percent more power output than a conventional inclined collector. Cottam et al. (Fig. 11[100]) investigated a series of canopy profiles for the optimal canopy layout and power output.

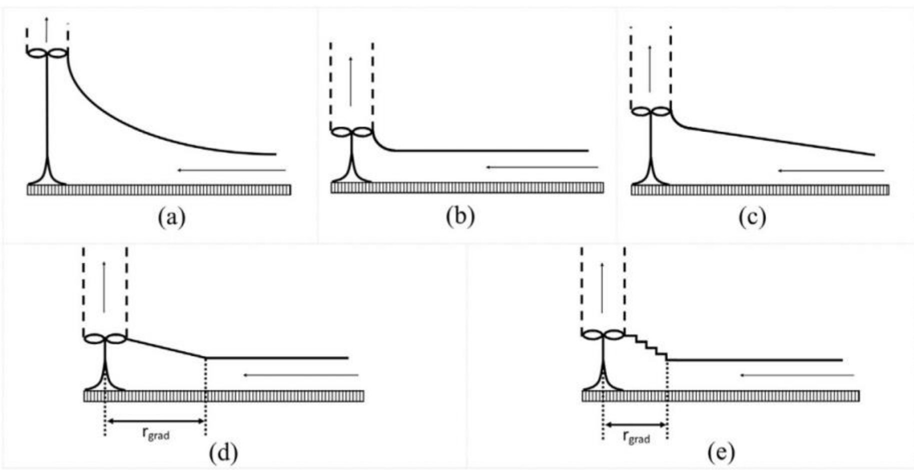

Fig. 11.Collector profiles: (a) exponential; (b) flat; (c) constant-gradient sloped; (d) segmented; and (e) segmented & stepped [100]

They compared the results for an exponential profile, a flat profile, a segmented profile, and a segmented with stepped profile, and reported that collector outlet height is an important parameter and could help control the pressure drop in the collector to chimney transition section. The adequacy of cross-sectional area in the transition section is a known determinative parameter for pressure loss. And even though an exponential profile has proved to be the best choice, Cottam et al. showed that a segmented collector profile could almost reach the performance of an exponential profile, but with a simpler design and lower cost. They also suggested a stepped segmented profile for good power output to construction cost balance.

3.2 **Accessories and Integrated Apparatus (Auxiliary Techniques)**

Many researchers have tried adding accessories to help improve the performance of SCPP systems; for example, supplementary apertures aim to enhance either the heat transfer or the flow field inside the solar chimney. Relating to this, Hosseini et al. [101] performed a numerical simulation to study the effects of longitudinal rectangular fins on solar chimneys, both in continuous and discontinuous fins. Comparing these to a flat absorber, Hosseini declared that, with appropriate interruption gaps, discontinuous fins could enhance the performance of solar chimneys over and above that produced from continuous fins. They showed that despite the dependence of efficiency to absorber area, the efficiency could still be improved by increasing the depth ratio of fins because the heat transfer area, and hence the net heat transferred to the airflow will be increased as a result. They also noted that disturbance and reformation of the boundary layer could lead to an improvement in the heat transfer coefficient but in the appropriate gap due to the effect declining in the absorber area. They also reported that increasing the number of fins would improve thermal performance. Hosseini et al. [102] also compared different shapes of fin, such as triangular, elliptical and rectangular in natural convection solar air heaters and declared that the thermal efficiency of a solar air heater with rectangular fins is 5.5% higher than those containing elliptical and triangular fins, and also that the thermal enhancement is strictly related to an increase in solar radiation and reduction of ambient temperature.
Following a different approach, Shabahang and Ghazikhani [103] studied the effect of passive flow control devices on solar chimneys. They implemented different obstacles shapes such as half-circle, rectangular and triangular obstacle shapes to alter the flow field and so improve inflow mixing using secondary flows and vortex generation. They also considered boundary layer agitation and fluid mixing as a contributor to enhancing the Nusselt number. They study observed improvements in all cases, but an obstacle with a triangular profile produced the greater thermal performance enhancement, because the flow pattern was not blocked, but rather was guided toward the chimney. Their passive control resulted in an increasing velocity rate and consequent energy output improvement of up to 41.2%. Further, Fallah et al. [104] evaluated the effect of artificial roughness on the ground as the air passes through the collector. They considered an optimal location for this artificial

roughness, which reduces air velocity but improves heat transfer compared to without-roughness collector cases. Hence, either from natural roughness (like the ground surface) or from the artificial roughness of a form of energy storage system, roughness has proved to make a valuable impact on solar chimney system performance. That being said, it has been suggested that installing artificial roughness near the collector entrance has no significant impact. So, to cope with the difficulty and limitations of a large installation field and higher collector efficiency, many researchers have applied different configurations and technologies to resolve this problem.

Pretorius (Fig. 12)[61] introduced a secondary roof integrated with an airflow regulation mechanism. In the Pretorius concept, the bottom section remains closed when less power is needed, and the system is in the ground energy-storing mode. At other times, the bottom section is opened, and flowing air captures the energy previously stored within the ground.

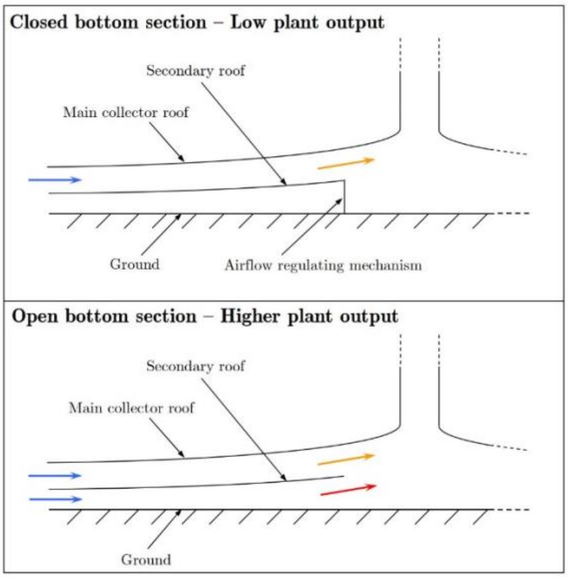

Fig. 12.Introduced a secondary roof collector by Pretorius[61]

Nasraoui et al. (Fig. 13) [105] suggested a novel collector design utilizing two flow paths. They developed a comparison between (a) standard configuration, (b) parallel in-flow channels and (c) counter in-flow channels. The results show greater improvement for the counter-flow case, but improvements occurring in both cases with parallel and counter-flow configurations to maximum velocity and temperature rise.

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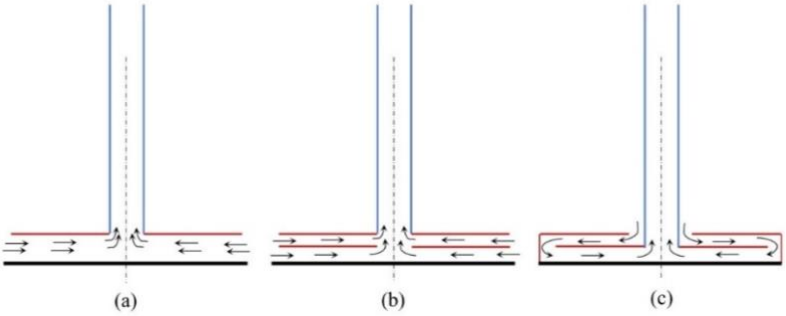


Fig. 13.Different configuration of novel collector design (a) standard collector; (b) double roofs collector with the parallel flow; (c)double roofs collector with counter flow[105]

Nasraoui et al. [106] predicted the effect of concavity in the collector by defining the function of the concavity ratio as the curvature radius of concavity in the collector roof divided by collector radius. They proposed that a concave collector could enhance the performance of the system and produce more power by increasing the concavity ratio of the collector, by which, understandably, the velocity inside the collector is increased (Fig. 14).

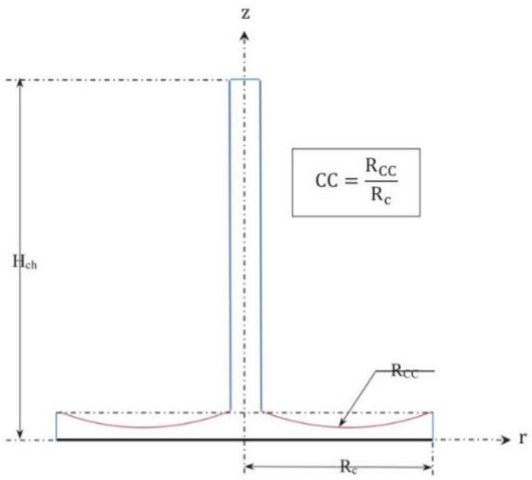


Fig. 14.Concavity ratio of a collector [106]

Rezaei and Imani [107] carried out a novel investigation on a small scale solar chimney setup utilizing intensifiers to increase heat flux on the collector and hence increase incoming irradiance. The layout is depicted in Fig. 15a. They also located an air tank downside the system to increase the absorption of solar radiation reflected by the intensifiers. In addition, a mechanical assembly was designed to allow the mirrors to traverse the orbital path in order to track all-day sun movement. They showed that, by using this apparatus, air velocity within can be chimney increased and this leads to greater power output. They recorded a maximum air velocity of 5.12 meter per second – which was remarkable for the test plant size – showing an approximate twofold increase compared to a without-intensifier prototype [108].

Faisal Hussain et al. [109] formulated an exergy and energy balance equation for the SCPP and observed maximum exergy destruction, and consequently the highest improvement potential, happens at the floor. They therefore proposed a new design of solar chimney with enhanced incident solar radiation aided with reflectors depicted in Fig. 15b. As a result, the efficiency gain was up to 22 percent compared to a conventional solar chimney, and all resulting from an almost ten percent increase in floor temperature.

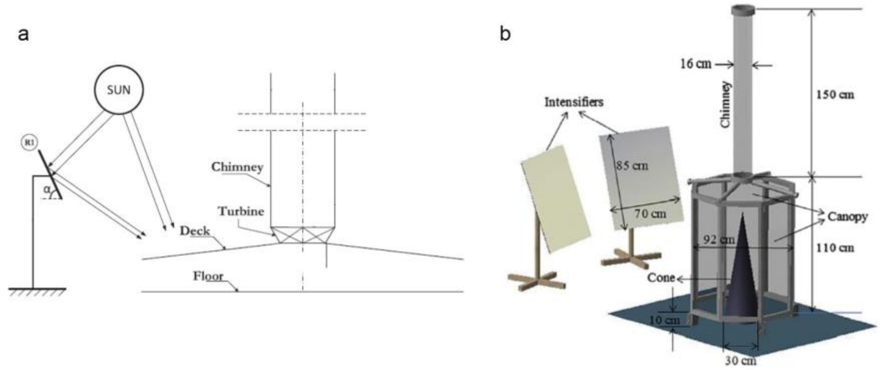


Fig. 15.A schematic of SCPP setup aided with intensifiers (a) Rezaei and Imani[107]; (b) Hussain and Al-Sulaiman[109]

Many authorities have reported that a main obstacle to designing very tall chimneys is that caused by the crosswind forces, and that these induce transversal stresses to the construction which need to be resolved for before successful commercializing. The design considerations have therefore caused a lot of difficulties for such rigid tall structures and produced many patents applications to cope with the problem. One such innovative configuration for a tall chimney has been proposed by Papageorgiou [110-117] (Fig. 16). In which, in order to reduce the chimney construction costs and resolve the difficulties, he utilized the merits of the airlifting force from an inflated fabric structure instead of a heavy rigid concrete body. The floating solar chimney (FSC) design therefore consists of an inner polyester fabric, associated with a twisted tube around it, which is then filled with lighter-than-air gas. He suggested either He or NH_3 as the filling gas to provide the role of the lifting force and proposed that such a floating solar chimney section could cope when combined to form super tall towers and be constructed for heights of up to 3000 meters. The folding lower part are also designed to bend freely against external winds and so can easily handle crosswind threats. It should also be noted that chimney height might be limited by annual average wind speeds and the potential deviation angle caused by prevailing crosswinds.

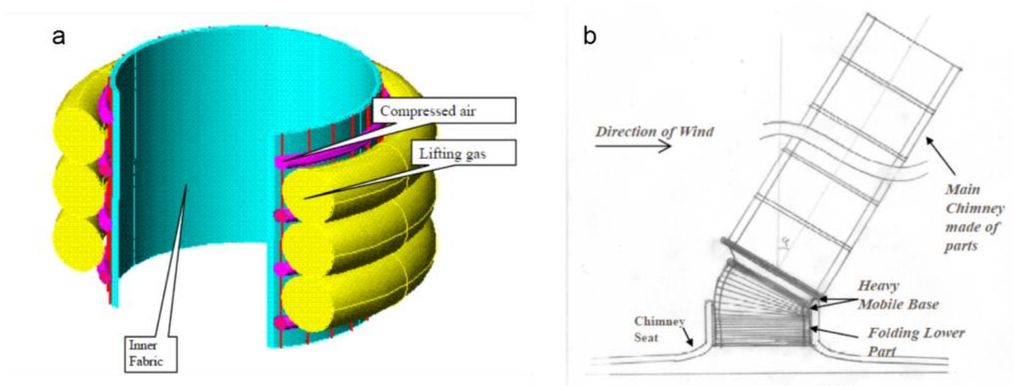


Fig. 16.(a) structure of FSC with over-pressed air tubes that retain its cylindrical shape and lifting gas tube to make a tall lighter than air cylinder[118]; and(b)configuration of FSC with folding lower part and floating chimney seat to deal with crosswind[113]

Zhouet al. [119] and Maghrebiet al. [120] also carried out an investigation into their economic aspects and estimated cosst. Maghrebi showed that these floating power plants are able to be constructed at large scale of up to 200 MW of electricity, with an annual capacity of 641 GW. In comparison, Putkaradze et al [121] suggested an innovative self-supporting, free-standing and flexible solar tower constructed with air-filled stacks as a replacement for a vulnerable tall steel chimney, as illustrated in Fig. 17. In their model, the chimney no longer has a straight cylinder geometry but can deform, and such deformations are not concentrated just in the base of the chimney – unlike the former design.

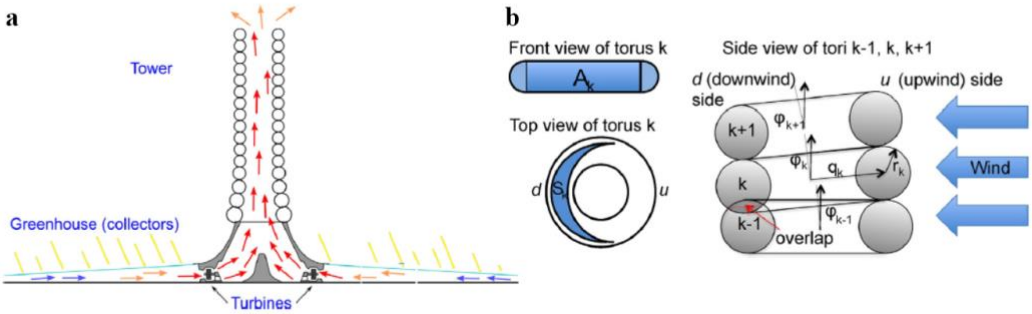


Fig. 17.Schematic of (a) solar chimney composed of toroidal bladders;(b) wind deformation mechanism shown[121]

An third interesting and novel concept was proposed by Li et al .[122], in which they suggested a combination of tornado type wind tower combined with a conventional SCPP. In this concept, the tornado type wind tower is positioned at the top of the chimney to exploit deficits of pressure and thereby increase the updraft driving forces. Li et al. showed the proposed prototype could decrease solar chimney power plant height by almost two times with a wind velocity of 15m/s. In conclusion, the hydrodynamic effect of wind speed enhances SCPP efficiency and could play a key role in solving one of the problems of tall chimney construction. The prototype is presented in Fig. 18.

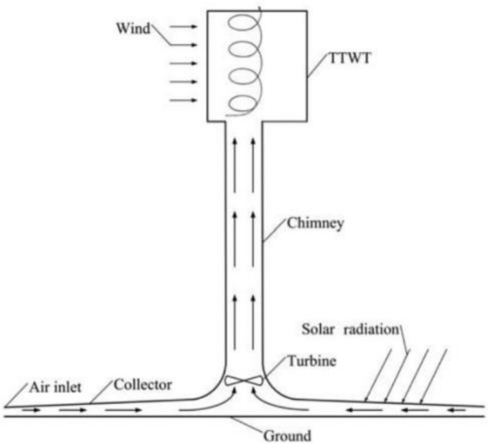


Fig. 18. Combined tornado type wind tower and SCPP concept [122]

Yet another suggested design to reduce chimney construction problems has been mentioned in Serag-Eldin's literature (Fig. 19a [123]).The goal being to exploit the height of a mountain as a replacement for very tall, vertical chimneys, and all with with no moving parts. With Serag-Eldin's proposal, the chimney utilizes the slope of the mountain, and runs up a ground-laid duct whilst the collector spreads over valleys. In fact, with such a design, the collector is limited to a semicircular geometry.

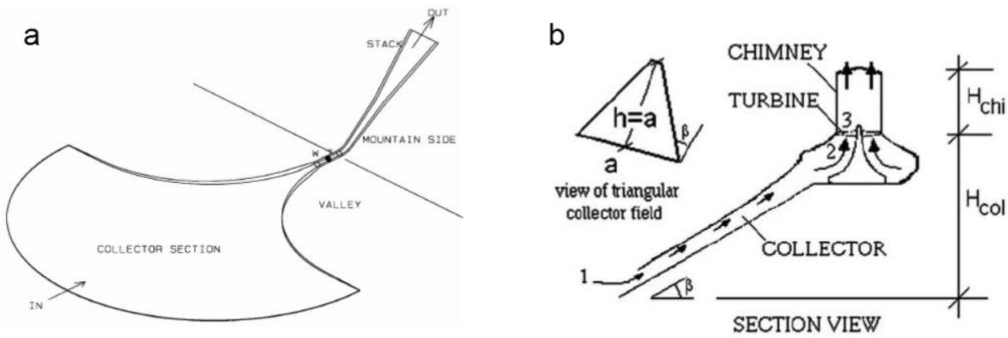


Fig. 19.Sketch of (a) proposed solar chimney design for mountainous regions[123]; and (b) solar chimney systems in a sloped surface at high latitudes[13].

Additionally, a sloped solar chimney has been produced by Bilgens (Fig. 19b [13]) for use in high latitudes, the main characteristic of this concept being a sloped triangular-section closed side collector which follows the line of the mountain or other natural slope. It was shown that this feature could then accept a solar chimney with height up to half the height of the collector [124]. Jing et al. investigated the best slope gradient in this area [125]. Some researchers [38, 126-129] also carried out performance analysis of these systems, comparing sloped solar chimneys, with conventional solar chimneys in China, Iran and other locations. Kalash et al.[130] investigated the temperature field of a sloped solar updraft power plant experimentally. Xinping Zhou [131] studied the best curved-profile fit for a mountain profile. He compared linear sloped collectors with a two-segment sloped collector and showed that the optimal sloping angle is lower than the local latitude. A further novel concept in this area has been presented by Zhou et al. [132]. Zhou [133] who suggested that a Solar Thermal Power Plant with Floating Chimney, rigidly mounted onto a Mountainside alleviate some of the difficulties of floating SCPPs, and make a smoother chimney line in mountain regions. The concept is shown in Fig. 20.

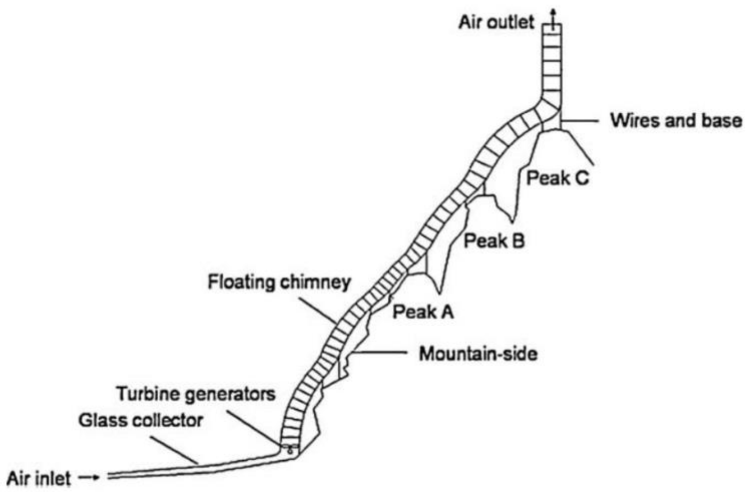


Fig. 20. Floating SCPP rigidly-mounted for a mountous region, schematic [133]

Papageorgiou (Fig. 21) [118, 134] proposed a modular Solar Collector for the solar chimney technology as a lower-cost alternative of the usual circular greenhouse pattern. The greenhouse will be made from a series of parallel reverse Vs or U-section glass panel tunnels leading to the entrance of the FSC. The modular solar collector diminishing on-site work and so lowering construction costs. It also could reduce dust problems and subsequent mud formation [135] which arise from a condensate film on the surface.

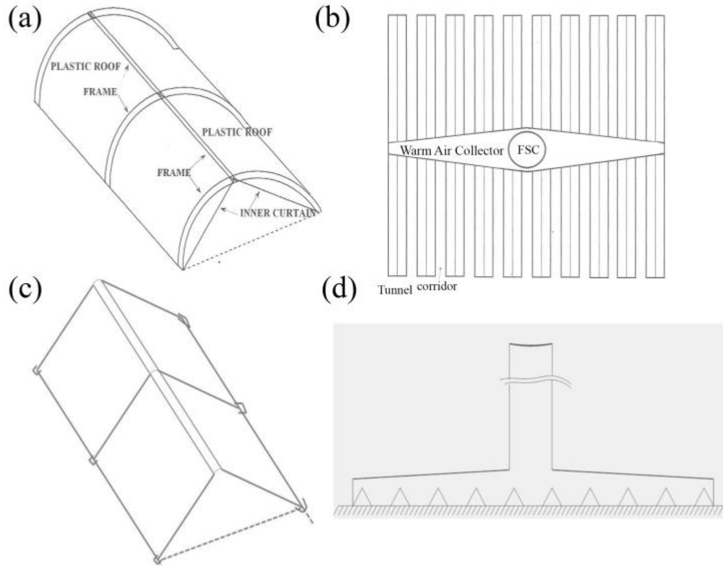


Fig. 21.Structural configurations of modular Solar Collector:(a)U type;(b)top view;(c)V type; and(d)front view[118]

Bonnelle [136] proposed a fresh concept to reduce turbulent friction inside the collector by utilising a series of branching ribs as shown in Fig. 22. Bonnell's design for the collector entrance, possessing a larger area than a conventional collector, leads to lower velocities and hence helps reduce turbulent friction losses. At the same time, the collector roof can be installed with a lower height, offering the opportunity for reducing costs.

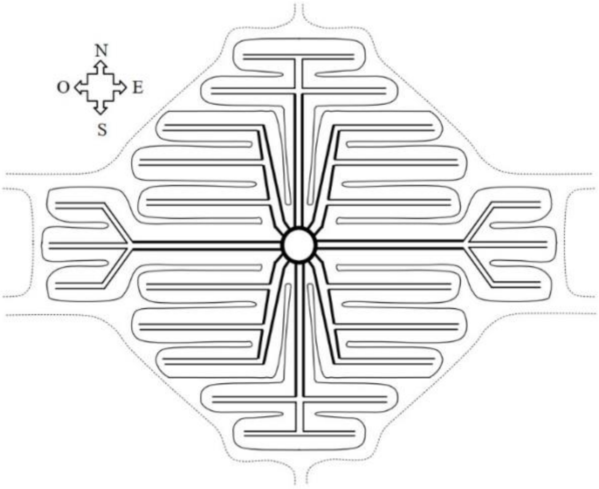
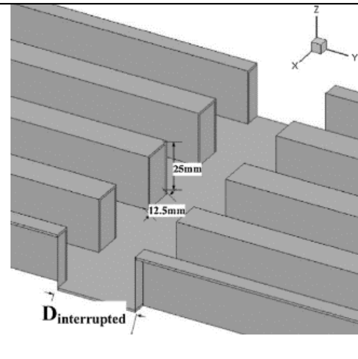
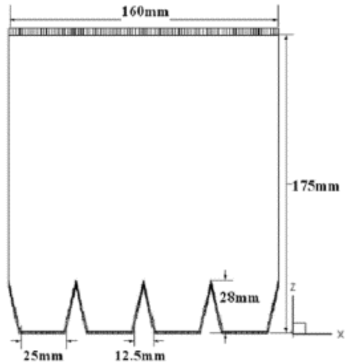
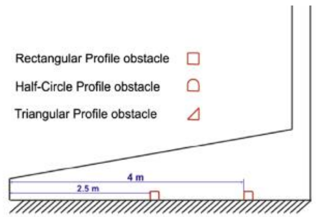
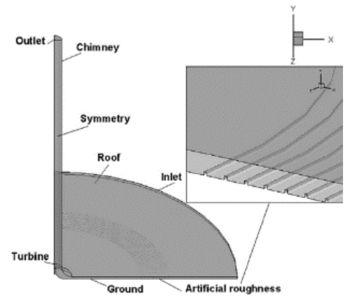
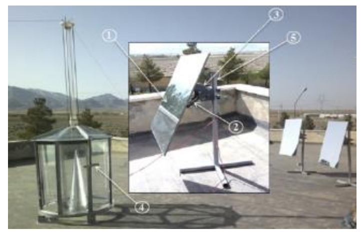


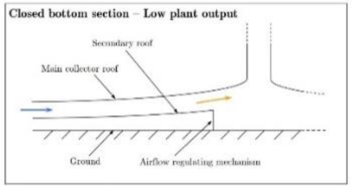
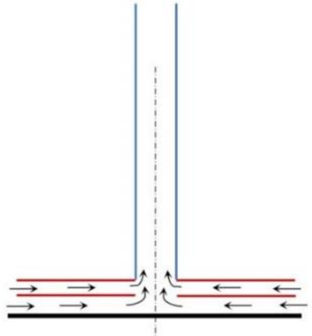
Fig. 22. Collector configuration with branching ribs [136]

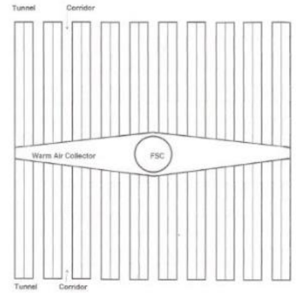
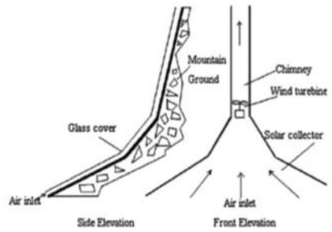
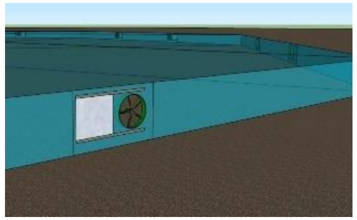
Papageorgiou [137] introduced a new concept to replace the gigantic chimney cross-section turbine by a series of controlled air opening in the collector inlet.
Wherein the collector inlet is encircled by a peripheral enclosure, and a series of axial air fans, controlled by microprocessors, are installed to provide a controllable flow inlet. Papageorgiou also suggested an electromechanical air stopping system in the opening to optimize power output by closing low-speed turbines. So that the residual air could be enhanced by the benefit of its now higher speed. Table 2 shows the advantages, disadvantages and prominent features of suggested auxiliary techniques.

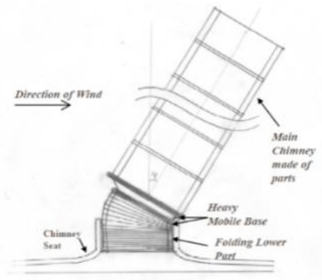
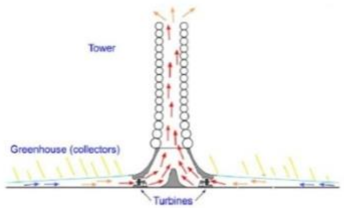
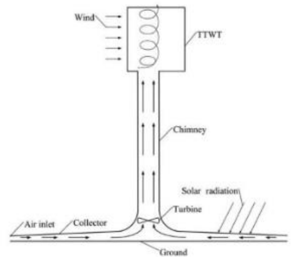
Table 2. Advantages, disadvantages and prominent features of suggested auxiliary techniques

	design	prescription	advantages	disadvantages	improvement	Schema	ref
Flow mixing enhancement	rectangular fin	Effect of longitudinal Continuous and discontinuous type of rectangular fin installation in absorber have been studied	-efficiency improvement by increasing the depth ratio of field (heat transfer area) -heat transfer coefficient improvement due to disturbance and reformation of boundary layer	-maintenance difficulties due to hard access inside the site -excess material usage in fins -higher pressure drop	- thermal performance improvement by the increasing number of fins - efficiency improvement by increasing the depth ratio of fins -performance enhancement in discontinuous type by appropriate interruption gaps		[101]
	Different fin shape	triangular, elliptical and rectangular fins effect in natural convection solar air heaters	-increasing thermal efficiency by redirecting the flow	-manufacturing difficulties in unconventional fin shape -maintenance difficulties due to hard access inside the site -excess material usage in fins -increasing in pressure drop	-The thermal efficiency of the solar air heater with rectangular fins is 5.5% higher than elliptical and triangular fins		[102]
	Passive flow control implementation	different shape obstacle implementation such as half-circle, rectangular and triangular	-altering the flow field and improve mixing inflow by secondary flows and vorticities.	-flow blockage in obstacles	- increasing velocity rate and consequently energy output improvement up to 41.2% - An obstacle with a triangular profile supplies more thermal performance enhancement since the flow		[103]

					pattern was guided toward the chimney.		
	artificial roughness	Considering the optimal location for artificial roughness due to velocity reduction despite heat transfer improvement	-either with natural roughness like ground surface or by artificial roughness such as energy storage system roughness has an inevitable impact - it can take advantages of existing component like water pipes - the existence of roughness has a positive impact on the performance of the power plant When the wind is blowing	-reduction in velocity	-installation artificial roughness near the collector entrance has a better influence in efficiency		[104]
Incoming radiation increase	Intensifiers utilization	utilizing intensifiers to intensify heat flux and air tank to increase absorption of reflected solar radiation	- higher heat flux entered the solar chimney by utilizing intensifier	-utilization in small SCPPsdue to collector shape and intensifier height limitation -ray tracing reflectors apparatus difficulties	-two times increment in maximum velocity compared with a without-intensifier prototype		[107]

	Reflectors utilization	A SCPPwith enhanced incident solar radiation aided with reflectors	-higher input flux temperature and mass flow rate	-limitation in reflectors high in large scale SCPPs	- the gain in efficiency was increased up to 22 percent compared to conventional solar chimney power, ten percent floor temperature increment and 134 percent increment in mass flow rate -133%power output increment		[109]
Secondary roof supplement	Transformative closure	Transformative end closure in underneath roof	-warm trapped air acting as an energy storage medium	-controllable mechanism difficulty for transformative end closure end			[61]
	Double roof	Parallel and counter flow mechanism	-more heating due to the longer path in counter flow type and exposed to warm air instead of ambient	-more pressure loss due to longer path			[105]

Novel collector design	Modular U type collector	Utilizing a series of long U or V type glasses	-prevent dust layer formation and consequent problems -low cost and with lesser working in site difficulties	-higher pressure loss			[138]
	sloped SCPP	Sloped SCPP along with mountain profile	-better companionship with mountain ups and downs -chimney behavior of collector due to rising				[126]
	Enclosed SCPPs	A closed collector entering containing a number of the axial fan instead of large scale turbines	-lower cost due to complex turbine section deletion such as gearbox -external wind altering - optimized power output by a controlled electro-mechanical air stopping system - convenient repair and maintenance	-low efficiency fans and numerous number of devices	- crosswind secured thermal storage layer		[137]

Novel chimney designs	Floating SCPP	Chimney filled with lighter than air gas make the possibility to lift off and tilting in cross wind	-relative negative pressure in outlet due to cross wind and providing good driving force -alleviating heavy solid problems -alleviating crosswind concerns	-lowering SCPP height in tilting operation mode			[113]
	toroidal bladders chimney	tubes with sliding possibility in cross wind interaction	-relative negative pressure in outlet due to cross wind and providing a good driving force -alleviating crosswind concerns	-lowering SCPP height in tilting operation mode			[121]
	Tornado wind tower combined	Tornado wind tower installed at the outlet to make a favorable driving force	-relative negative pressure in outlet and providing good driving force -ability of utilizing smaller SCPPs	-low improvement in low wind speed region	-providing power output up to a twice height size		[122]

3.3 Hybrid SCPPs

Because sunlight is not available for all hours of the day, and is also reduced on cloudy days, scholars have considered how to reduce these effects and allow some form of 24-hour operation without intermittency. There are reports on combining technologies, for example, using fuel cells, thermal energy storage, geothermal effects, photovoltaic cells, wind power technologies etc., with solar, so creating multi-objective systems such as water desalination and solar drying procedures etc.

3.3.1. Desalination

Desalination of impure water is one simple, cheap and useful way of using brackish water. However, water desalination is limited by factors such as the need for large-area solar distillation plants, low water production rates per unit area and the natural restriction of limited solar radiation in some regions [139]. According to the report from International Water Association (IWA) published in 2016, water desalination can cut costs (as shown in Fig. 23), since it is becoming an effective way of solving water demand problems in areas with high water salinity level [140-142]. However, at this time, integrated SCs with water desalination are not yet practical and this promising hybrid needs further studies. That being said, cost forecasts over the next 15 years, show a considerable reduction in construction costs, electrical energy usage etc., as shown in table 3.

Table 3.Costs of desalination for medium and large projects[142].

Parameter for Best-in Class Desalination Plants	Year 2016	Within 5 Years	Within 20 Years
Cost of Water (US$/m^3)	0.8 – 1.2	0.6 – 1.0	0.3 – 0.5
Construction Cost (US$/MLD)	1.2 – 2.2	1.0 – 1.8	0.5 – 0.9
Electrical Energy Use (kWh/m^3)	3.5 – 4.0	2.8 – 3.2	2.1 – 2.4

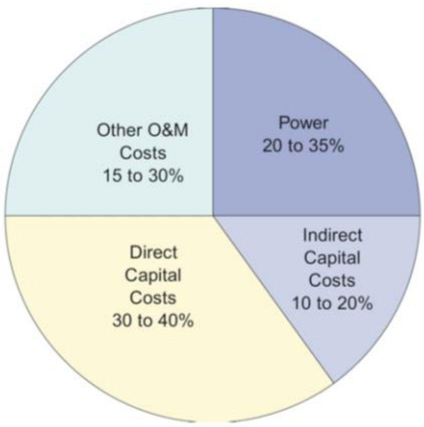


Fig. 23.Desalination cost breakdown[142].

Zou et al. evaluated two types of hybrid systems, 1) a wind supercharging SCPP with seawater desalination and waste heat, 2) SCPP integrated with seawater desalination and waste heat [143]. They investigated the proposed models both experimentally and mathematically to estimate the efficiency of hybrid systems. The results in the research of Zou et al. are as shown in table 4.

Table 4. Comparing results and the evaluated parameters by Zou et al. [143]

Investigated parameter	Results	Comparison
Increase in chimney's height	Water desalination improved Power generation improved	---
Increase in solar irradiance	Water production decreased Generated power improved;	---
Decline in seawater depth while enough solar irradiance exists	Water desalination improved Power generation improved	---
Increase in the temperature of the exhaust gas	Water desalination improved Power generation improved	---
Performance	---	WSCPPDW was better than SCPPDW about 15%

3.3.2. Drying Technology

Solar drying dates back to 8000 BCE, when the first solar dryer was installed in France. In an energy conscious world, solar drying is becoming a necessity because of its major merits, such as no requirement for fuel or electric power. Drying is an activity which consumes lots of energy in its broader productions applications, for example, textile manufacture [144], brick production [145], cement production [146], and wood and timber treatment [147] etc. Solar drying therefore offers yet another option for switching to a more eco-friendly method rather than using fossil fuels. Sandali et al. reviewed the enhancement of solar drying system by various techniques and factors in multiple solar dryers, such as direct, indirect, mixed-mode and hybrid dryers [148]. At the same time, the effect of different climate conditions, geometry, heat exchanger and heat pumps, reflector addition, phase change material (PCM) and etc. were also evaluated. The results of which, showed that climate conditions and solar radiation had the greatest impact.

Afriyie et al. investigated the performance of a solar dryer experimentally [149]. In their research they performed their tests firstly in a cabinet dryer, followed by tests with a chimney. Eventually, the trials were conducted with a tent dryer in which the roof of the drying chamber was inclined. Afriyie et al. also monitored effective factors such as air velocity, temperature, relative humidity and the moisture content in a crop.

Afriyie et al. divided their experimental tests into two different categories, namely no-load and under-load tests. In the under-load category, there were 4 different subcategories as follows:

- Test-set 1: tests on the dryer with roof angle 81°, using the normal chimney.
- Test-set 2: a repeat of Test-set 1, but with the solar chimney.
- Test-set 3: using the roof angle of 64°, still with the solar chimney.
- Test-set 4: using the roof angle 51°, still with the solar chimney.

Under-load tests were conducted in the presence of the root crop cassava.

In table 5 shows the dryer no-load conditions.

Table 5. Conditions of the dryer in no-load tests [149].

	No absorber	**With chimney absorber**		
	`Test-set 1	Test-set 2	Test-set 3	Test-set 4
Roof angle (°)	81	81	64	51
Ambient air temperature (°C)	21.83	23	22.17	23.5
Dryer exit air temperature (°C)	26.83	31.33	29.5	30.83
Inlet air relative humidity (%)	57.17	42.17	51.67	42.33
Dryer exit air relative humidity (%)	38.17	26	34.17	24.83
Ambient air velocity (m/s)	0.02	0.01	0.02	0.01
Dryer inlet air velocity (m/s)	0.14	0.18	0.19	0.2
Dryer exit air velocity (m/s)	0.39	0.45	0.49	0.52

Afriyie et al. concluded that a solar chimney crop dryer is advantageous because it is cheap to construct, and that its performance is enhanced when the relative humidity of the ambient air falls. However, conversely, performance is reduced when relative humidity is high [149].

3.3.3. Photovoltaic Cells and SCPPs

Rahbar and Riasi proposed novel configurations of conventional solar chimney power plants (CSCP) coupled to a photovoltaic cell (PVSCP) and brackish water desalination (PVDSCP) in order to utilize solar energy more effectively [150]. In their study, Rahbar and Riasi developed a 1-D mathematical model for each configuration and then validated their mathematical results by experimental results. The studied geometry is shown in the Fig. 24.

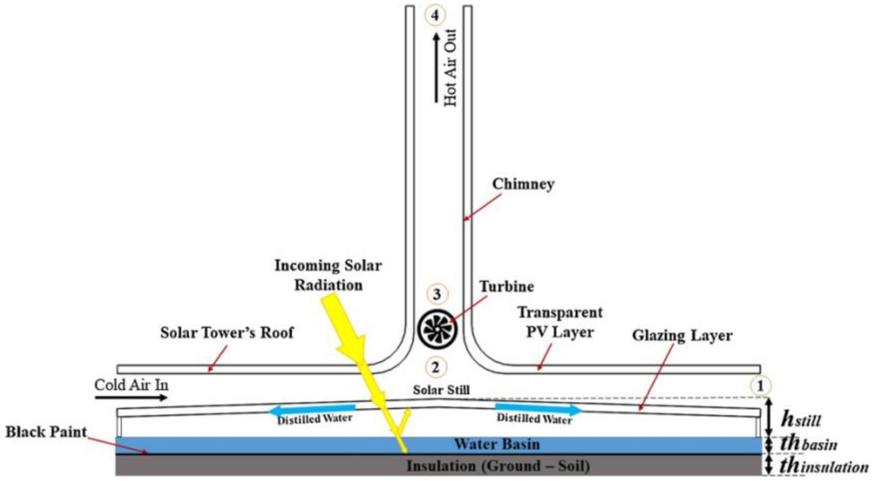


Fig. 24. Schematic detailed geometry of the PVSCP and the PVDSCP [150].

From their results, it is revealed that a PVDSCP is more efficient than a CSCP and a PVSCP by 26.13% and 21.92%, respectively. In contrast, the efficiency of the turbine is higher than the CSCP and PVDSCP by about 17.9% and 31.3%, respectively. Key parameters in their optimization were the roof radiation, roof height, tower radiation, tower height, and mass flow rate. After comparing the optimization with the Manzanares solar chimney power plant[36], their results showed that utilizing a PVSCP and PVDSCP in Manzanares could improve the efficiency of the power plant, 55.97%, and 71.8%, respectively.

Using fluid dynamic analysis Haghighat et al., evaluated different PV panels in four different locations in a SC [151], and their investigated parameters (as shown in Fig. 25), included the location and the widths of the PV panels within the SC. Three different PV widths of 70, 50, and 30 cm were tested and the 50 cm cell proved to offer the best results, in that when the transparent collector was replaced with the 50cm width PV cell, the efficiency is increased by 1%.

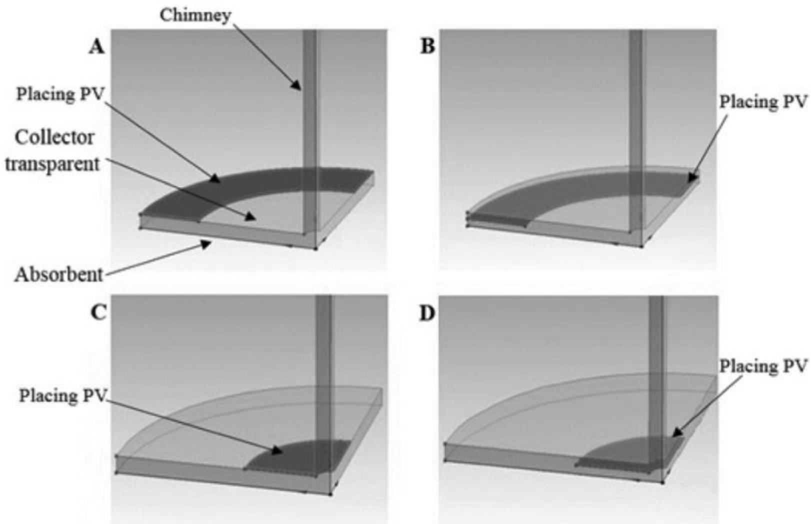


Fig. 25.Investigated parameters by Haghighat et al.[151].

Ahmed et al. proposed a new design for a chimney in Kirkuk, Iraq [152] by constructing two types of experimental model. In the first model, the collector roof is made of a glass and a PV panel was installed as an absorber, whilst in the second model, the collector roof was made of PV panels and used plywood as the absorber. They observed that the useful power from the second model's was greater.

3.3.4. Ventilation

In applications related to ventilation, the most examined parameter is the air flow rate. Nguyen and Wells analyzed the flow rate and thermal efficiency of using hybrid SCs to ventilate buildings through CFD simulation [153], their evaluation dimensions being chimney length, air channel gap, inlet height, outlet height, inlet width, and outlet width. Results showed an increase in flow rate is possible with increased absorber surface length, air channel gap, and the heat flux, but a drop in thermal efficiency for the outlet width – due to flow reversal at the outlet.

Serageldin et al. performed a parametric study, which included optimization methods for heating and ventilation systems through CFD, as shown in Fig. 26 [154]. In this research, they validated their results against an experimental result in the cold season on March 14-22, 2016 in Egypt.

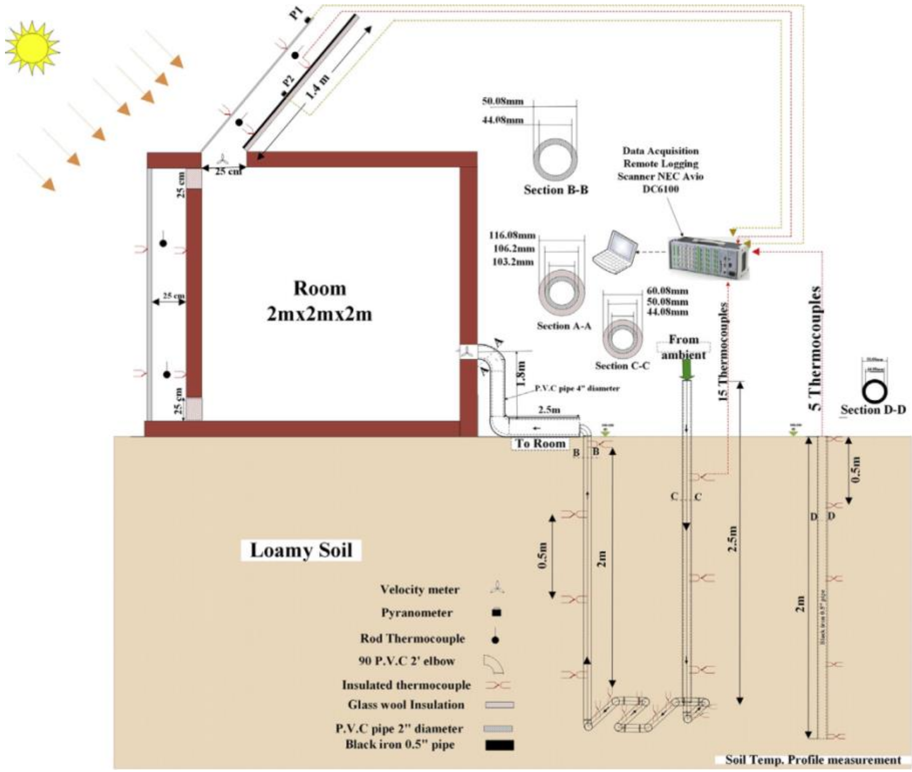


Fig. 26. Schematic of the studied geometry by Serageldin et al. [154].

In their investigation, they optimized the system through the central composite design of the experiment (CCD) algorithm, and found eight parameters to maximize the ventilation rate for the solar chimney configuration and earth-to-air heat exchanger design, these being: width, length, air gap, inclination angle, position and pipe diameter, inlet position, and inlet height. The most sensitive parameters being (in order), EAHE pipe diameter, chimney height, EAHE height and position, solar inclination angle, width, and gap. They also concluded that the optimum chimney inclination angle, length, width, and gap, lie within ranges of 30–35°, 1.94–1.97 m, 0.92–0.97 m, and 0.19–0.23 m, respectively.

Kong et al. examined the variation of the inclination angle of a SC installed on a roof, looking to enhance its performance for ventilation purposes using CFD based methods. The work considered two cities in Australia – Adelaide airport, Darwin, and Townsville Aero [155], and Kong et al. performed their simulations under four different heat fluxes, 200, 400, 600 and 800 W/m^2, together with the impact of various inclination angles, $30°, 45°, 60°, 75°$ and $90°$, respectively. They reported two main conclusions as follows: 1) In real-life related applications the inclination angle exerts a profound influence on the received solar irradiance and the ventilation efficiency. 2) In their numerical evaluation, the greater inclination angle, the greater the space ventilation.

Wang et al. described a hybrid SC for ventilation [156]. They examined 4 main parameters through a CFD approach, namely the thickness of the glass panel, the width of the air gap, the thickness of the water columns and surface tinting. Their results showed that by cutting the thickness of the glass panel in half, the ventilation was enhanced by 7.3%. In addition, that up to 0.2 m increase, either in the width of the air gap or the thickness of the water column, boosted the ventilation rate by 21%.

3.3.5. Power Generation

Electrical power is generated through a complex heat transfer process where solar energy is converted to electrical power. Coupling turbine blades with a SC can generate power which is a free and durable source for power generation and Tingzhen et al. numerically analyzed a SC coupled with a turbine [157]. In their study, they investigated the effect of turbine rotational speed on the outlet of the chimney. They also considered, by simulation, the design and performance of a MW-graded SCPP with a 5-bladed turbine. The results showed an efficiency of 50% at a power output of 10 MW.

Xu and Zhou developed a mathematical model for their performance investigation into a modified solar chimney power plant (MSCPP) used for power generation and vegetation growth purposes, the schematic for which is shown in the Fig. 27 [17]. The evaluated parameters were solar radiation, ambient temperature, relative humidity, and chimney height.

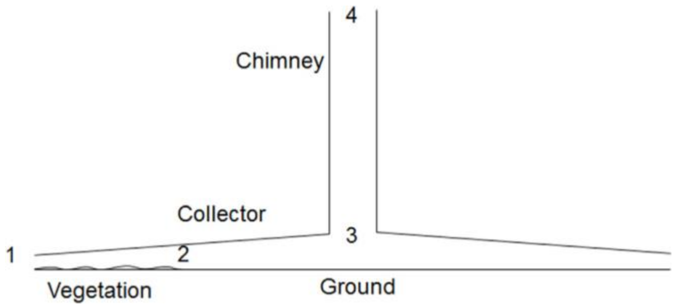


Fig. 27. Schematic of modified solar chimney power plant, vegetation is grown in some parts of the collector [17].

They validated their simulation results via the experimental results of Haaf [36]. Results show that an increase in vegetation area results in an increase in the mass flow rate of the vapour and leads to a considerable reduction of the power. Furthermore, when the weather is cooler, the production of power also falls. Further, when the relative humidity is higher, the mass flow rate of the evaporated vapour from the vegetation area decreases, but power generation increases. Finally, they concluded that a modified solar chimney power plant is more advantageous than a conventional SCPP.

Wahab and Al-Maliki studied the capability of utilizing a SCPP in a farm to produce electrical power for agricultural demands, such as pumping systems, irrigation, and lighting etc. The study was performed using Ansys software and was compared with the results obtained from an experimental farm condition [158]. Wahab and Al-Maliki concluded that the experimental farm SCPP, with collector dimensions of 70 m × 50 m and the chimney height of 20 m, had produced electrical power at its highest level in a year, at about 29 kW [158].

Tian et al. analyzed a hybrid SC in a desert city, Yazd, located in Iran [159]. In this research, they optimized the SC economically using a deer hunting optimization algorithm whilst comparing these optimization results with the genetic algorithm and particle swarm algorithm of MATLAB software. Tian et al. proposed two days, in July and in February, in order to analyze the hottest and the coldest days in the desert region of Yazd. From the results, they concluded that on the hottest day in July, owing to the high intensity of the sunlight, the produced energy is comparable with the coldest day in February.

3.3.6. Wind Turbine

Negrou et al. investigated the thickness distribution of blades and the desired swirl distribution [160] which was proposed by Wu [161]. The goal of their research was to design the turbine blades, based on the dimensions of the existing prototype suggested by Manzanares [5], which then speeds up the optimization design for a SC. Also, incompressible non-viscous flow was studied as part of this their research. Fig. 28 shows the studied geometry and the generated mesh in their model.

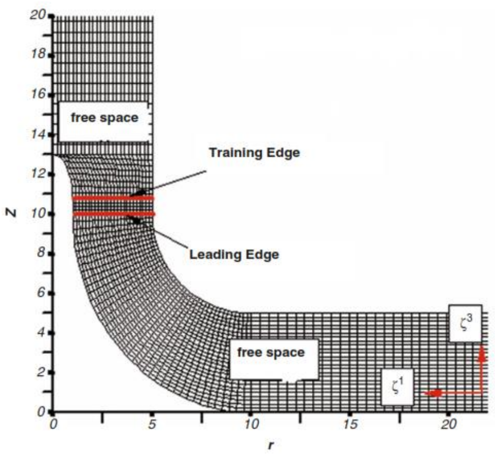


Fig. 28. Studied geometry by Negrou et al. [160].

3.3.7. Cooling Systems

Nasri et al. designed a new system based on the integration of a SC and a solar-air conditioning system [162]. The system works upon the principles of adsorption chilling and desiccant dehumidification, and as part of the investigation, the authors theoretically considered the proposed system under real conditions related to Tunisia. The test was performed on 4 different days, and on each occasion the air temperature decreased, and the relative humidity increased during the pre-cooling and cooling processes, respectively.

Hweij et al. studies the efficiency enhancement of cooling a window using a solar chimney, analyzing and predicting the window temperature and its impact on comfort under the conditions in an office space located in Riyadh, Saudi Arabia[163]. There were two representative hours, 14 h and 17 h, for this hot, dry climate. The results showed that thermal comfort was improved by the provided system. When the system was present at 14 h, the thermal comfort reaches 1.42. However, and for comparison when the proposed system was absent, in order to reach the same level of thermal comfort (1.42), a similar space was considered where all the conditions were constant, but the supply temperature was kept variable. Likewise, when the system was present at 17 h, the comfort level was 1.96 The work showed that the proposed system saves energy by approximately 10% (see Table 6).

Table 6. Saved energy at 14 h and 17 h [163].

Cases	Overall thermal comfort	Energy-saving (%)
14 h	1.42	9.64
17 h	1.96	9.8

3.3.8. Water Harvesting

Ming et al. suggested a modified solar chimney that can generate freshwater in addition to generating power [164] and the proposed chimney design has undergone experimental tests within nine different cities in China. The work looked at the moist air which condenses above the lifting condensation level, and of a one-dimensional compressible flow and the heat transfer mathematical model developed. The work showed a direct correlation between the precipitation of the environment and the produced water by this system – in general the modified system increasing water production by a coefficient of 0.875. Furthermore, they observed that the system is also effective in arid regions, and Table 7, indicates a convincing increase in the ratio of water production to natural precipitation across all nine cities.

Table 7. Natural precipitation (NP), water production (WP), and the ratio of WP/NP at nine stations in 2013 [164].

	NP (mm)	WP (10^4t)	WP (mm)	Ratio (WP/NP)	Sunshine duration (h)
Chengdu	1343.3	29.71	5942	4.42	1128.8
Shanghai	1173.4	23.62	4724	4.03	1864.7
Shijiazhuang	508.3	17.08	3416	6.72	1716.8
Zhengzhou	353.2	12.87	2574	7.29	1925.6
Wuhan	1434.2	29.37	5874	4.10	2092.5
Chongqing	1026.9	27.40	5480	5.34	1213.7
Beijing	579.1	14.59	2918	5.04	2371.1
Urumqi	300.9	8.18	1636	5.44	3068.6
Guangzhou	2095.4	37.92	7584	3.62	1582.9

Wu et al. proposed a modified solar chimney power plant, called a "Aero logical Accelerator" (AeAc), which utilizes the latent heat of a condensation process [165]. Using a mathematical model, the potential energy and generated water at different ambient temperatures were conducted, and their results (Fig. 29), show that the system can generate both water and electrical energy for domestic usage if the right method is used for collecting the water. As such, electrical energy generation depends on the temperature of the entering heated air and the system size. Furthermore, water generation is determined by the relative humidity at the entrance of the chimney in addition to the aforementioned factors.

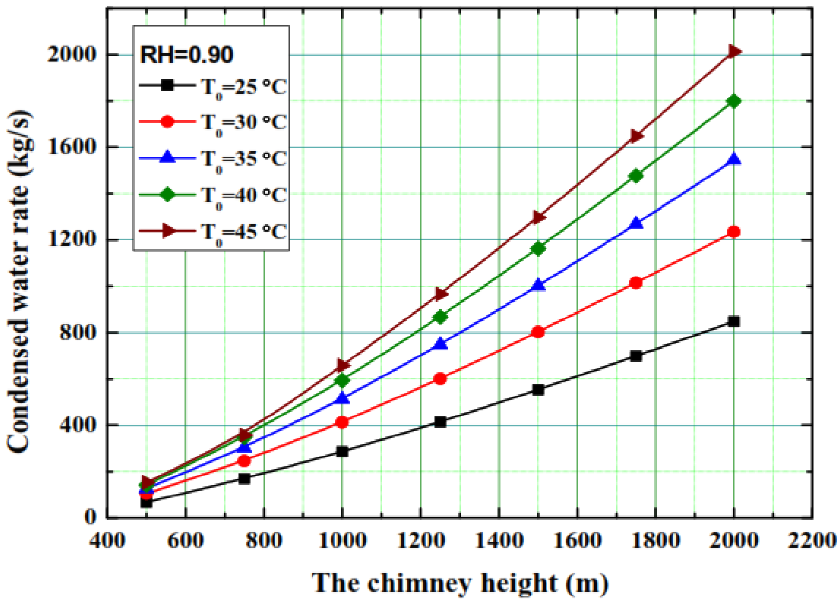


Fig. 29. Rate of condensed water vs. chimney height at RH= 0.90 [165].

Hoseini and Mehdipour numerically analyzed the effect of solar radiation and water temperature on power generation and water harvesting for two different cases, namely (1) integrating a SC with a humidifier and (2) coupling a chimney with a humidifier and a condenser [166]. In the conducted research, they concluded that, in the first case, by utilizing a hybrid SC, the generated power rises with increasing solar radiation, and that it increases at least 1.3 times higher than with a typical SC when the water temperature is at a minimum of 10 ℃. With the second case, they found that as solar radiation grows, the amount of harvested water declines.

4. Conclusion

Solar chimney power technology is a simple thermal technology involving three main components: The Solar Chimney, the Solar Collector and a Power Conversion Unit. However, despite being a straightforward and eco-friendly technology, its low efficiency remains an important practical drawback. Accordingly, solutions to this problem have drawn much attention in order to harvest greater power output and lower spending costs. This work aims to present a comprehensive, and for the most recent, detailed and applicable studies including experimental, theoretical, simulation and reviews which cover new design concepts along with configuration suggestions for efficiency increments.

The crucial point that emerged from the experimental studies, is that most of the constructed SCPPs are built at a small scale, and are not capable of utilizing potential improvements that are inherent with larger economies of scale because most of the system parameters are strongly dependent on the constructional problems that would occur with larger scale plant, such as chimney divergence angle. However, despite their low efficiency (for SCPPs, less than 2%), some researchers have focused on improving the overall efficiency through the enhancement of individual parts of the system. Hence with such an aim in mind, many design parameters have been considered within each section, including changes to profile – both chimney and collector segment. Novel ideas such as utilizing fins, obstacles, reflectors and a secondary roof for the collector, for a floating chimney, for different profile shapes and new chimney configurations have been reviewed as well.

In some studies, the low-efficiency imperfections have been reduced by integrating an SCPP other systems, and these are categorized into 8 main groups, namely: 1) Water Desalination Systems, 2) Drying Products, 3) PV Collectors, 4) Ventilation Systems, 5) Power Generation Systems, 6) Geothermal SC, 7) Cooling Systems, and 8) Water Harvesting. Water desalination can reduce the costs of providing water in some arid regions. The integration of SCPPs and dryers is not an option since solar energy is an eco-friendly, durable and free source. The other types of hybrid SCPPs are power generating SCPPs which can generate electricity from the sun by a simple replacement in the collector, e.g. installing turbine blades in the SC. Ventilation in buildings and chilling systems is another usage of hybrid SCs which can enhance the efficiency of the ventilation and the cooling system in addition to generating free power. The other important function of hybrid SCs is water harvesting that is one possible solution to the ever-increasing problem of the water crisis which is spreading across the world.

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