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A Review of solar Chimney Power Generation Technology

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Abstract-The present paper presents an overview of the main characteristics of a novel kind of solar thermal application called solar chimney power plant. It is a technology of electric power generation using solar energy by employing basic physics that when air is heated it rises. The created updraft can be used to turn a turbine placed at an appropriate position within a tall chimney to generate electricity. The paper discusses the principles and characteristics of such a system, its requirements, its construction and its operation. It also focuses on actual research and development of solar chimney projects.

Index Terms— projects, power generation, solar chimney, solar energy.

I. INTRODUCTION

At present, a number of energy sources are utilized on a large scale such as: coil, oil, gas and nuclear. Continuation of the use of fossil fuels is set to face multiple challenges namely: depletion of fossil fuels reserves, global warming and other environmental concerns and continuing fuel price rise. For these reasons, the existing sources of conventional energy may not be adequate to meet the ever increasing energy demands. Consequently sincere and untiring efforts shall have to be made by the scientists and engineers in exploring the possibilities of harnessing energy from several non-conventional energy sources (solar, biomass, tidal, hydrogen, wind and geothermal energy) which they are seen as possible solution to the growing energy challenges. According to energy experts, unconventional energy sources can be used for electric power generation which receives a great attention [1]. Power generating technology based on green resources would help many countries improve their balance of payments.

Being the most abundant and well distributed form of renewable energy, solar energy constitutes a big asset for arid and semi-arid regions. A range of solar technologies are used throughout the world to harvest the sun's energy. In the last years, an exciting innovation has been introduced by researchers called "solar chimney". It is a solar thermal driven electrical power generation plant which converts the solar thermal energy into electrical power in a complex heat transfer process. The implementation of this project is of great significance for the development of new energy resources and the commercialization of power generating systems of this type and will help developing countries to promote the rapid development of the solar hot air-flows power generation [2].

The basic physical principles of centralized electricity generation with solar chimney power plants (SCPP's) were described by Haaf et al. [3, 4] in 1982. After the pilot plant in Manzanares had gone into operation in June 1982, the first experimental results confirmed the main assumptions of the original physical model [3,5]. Later, on the basis of experimental data from July 1983 to January 1984, a semi-empirical, parametrical model was proposed for predicting the monthly mean electrical power output of the pilot plant as a function of solar irradiation [6]. The model predictions agreed reasonably with the experimental data for the exceptionally dry months July- October 1983, but the model failed to simulate the wet months following heavy rainfall in winter and spring 1984. It was realized, that natural precipitation entering the collector has a fundamental influence on the collector performance via evaporation, plant growth and infrared absorption in the collector air [3].a refined parametrical model was therefore proposed, which includes at least the long term, seasonally varying effect on rainwater on the plants performance and allows the simulation of large plants in climates similar to the climate in Manzanares [7]. The cost of electricity generation were estimated in [3,7] and calculated in details in [7].

II. HISTORY

Many researchers around the world have introduced various projects of solar tower. Around 1500, Leonardo Da Vinci made sketches of a solar tower called a smoke jack (see figure 1-a) [8]. The idea of using a solar chimney to produce electricity was first proposed in 1903 by the Spanish engineer Isodoro Cabanyes (figure 1-b). Another earlier description was elaborated upon in 1931 by the German science writer Hans Gunther [9]. He proposed a design in the 25 August 1903 issue of "La Energia Eléctrica", entitled "Projecto de motor solar". In this bizarre contraption, a collector resembling a large skirt heats air, and carries it upwards towards a pentagonal fan inside a rectangular brick structure vaguely resembling a fireplace (without a fire). The heated air makes the fan spin and generate electricity, before it escapes up a 63.87 m tall chimney, cools, and joins the atmosphere [10]. In 1926, Prof Engineer Bernard Dubos proposed to the French Academy of Sciences the construction of a Solar Aero-Electric Power Plant in North Africa with its solar chimney on the slope of the high height mountain after observing several sand whirls in the southern Sahara (figure 2 -3) [11].

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The author claims that an ascending air speed of 50 m/s can be reached in the chimney, whose enormous amount of energy can be extracted by wind turbines [12].

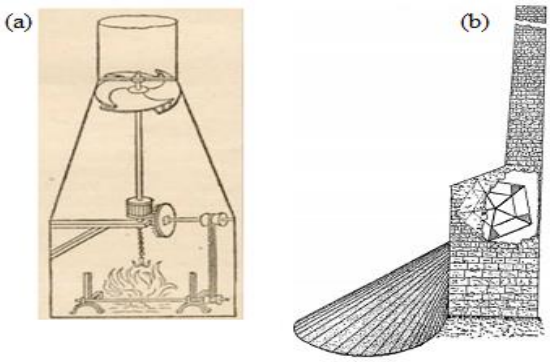

Fig.1.(a) The spit of Leonardo da Vinci (1452-1519) (Library of Entertainment and Knowledge 1919). (b) Solar engine project proposed by Isodoro Cabanyes.

The academy recommended the Dubos's idea be followed up, especially in French North Africa, which has no fuel and needs power. As a matter of fact Dubos had the North African Atlas Mountains in mind when he developed his plans [12].In 1956, he filed his first patent in Algeria. It was artificially generate ancestry atmospheric vortex in a sort of round-shaped Laval nozzle and recover some energy through turbines. Nazare received a French patent for his invention in 1964 (figure 4) [11]. In 1975 the American Robert Lucier filed a patent request based upon a more complete design. This patent was granted in 1981 [11]. Starting in 1982, a team led by the German civil engineer Jörg Schlaich took the initiative and constructed a prototype in Manzanares Spain, with a 200 m high and a maximum power output of 50 kW [13]. In 2002 Time Magazine identified this project as one of the best inventions of the year. The operating principle is considered revolutionary but is based on very common knowledge: Warm air rises [9].

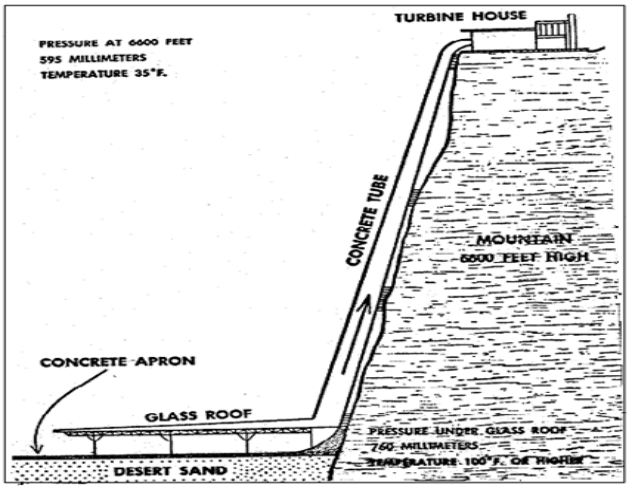

Fig.2.Principle of Professor Dubos's power plant.

Fig.3. solar chimneys in the Moroccan desert envisioned by Dubos.

Fig.4. the solar tower of the professor NAZARE. (Source: L'Ere nouvelle n° 52 July 1985)

III. WORKING PRINCIPLE

As presented in the figure 5, a Solar Updraft Tower converts solar radiation into electricity by combining three well-known principles: the greenhouse effect, the tower and wind turbines in a novel way. Hot air is produced by the sun under a large glass roof [14]. Direct and diffuse solar radiation strikes the glass roof, where specific fractions of the energy are reflected, absorbed and transmitted. The quantities of these fractions depend on the solar incidence angle and optical characteristics of the glass, such as the refractive index, thickness and extinction coefficient. The transmitted solar radiation strikes the ground surface; a part of the energy is absorbed while another part is reflected back to the roof, where it is gain reflected to the ground. The multiple reflection of radiation continues, resulting in a higher fraction of energy absorbed by the ground, known as the transmittance-absorptance product of the ground. Through the mechanism of natural convection, the warm ground surface heats the adjacent air, causing it to rise. The buoyant air rises up into the chimney of the plant, thereby drawing in more air at the collector perimeter and thus initiating forced convection which heats the collector air more rapidly. Through mixed convection, the warm collector air heats the underside of the collector roof. Some of the energy absorbed by the ground surface is conducted to the cooler earth below, while radiation exchange also takes place between the warm ground surface and the cooler collector roof. In turn, via natural and forced convection, the collector roof transfers energy from its surface to the ambient air adjacent to it [13]. As the air flows from the collector perimeter towards the chimney its temperature increases while the velocity of the air stays approximately constant because of the increasing collector height. The heated air travels up the chimney, where it cools through the chimney walls. The chimney converts heat into kinetic energy. The pressure difference between the chimney base and ambient pressure at the outlet can be estimated from the density difference. This in turn depends upon the temperatures of the air at the inlet and at the top of the chimney. The pressure difference available to drive the turbine can be reduced by the friction loss in the chimney, the losses at the entrance and the exit kinetic energy loss [14]. As the collector air flows across the turbine(s), the kinetic energy of the air turns the turbine blades which in turn drive the generator(s) [13].

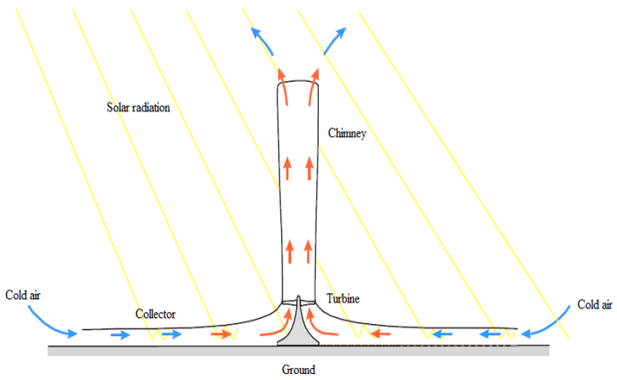

Fig.5. Solar chimney power plant description.

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IV. SOLAR CHIMNEY COMPONENTS: CONSTRUCTION AND MATERIALS

A. Collector

The major component of a solar chimney power station is the solar collector. Solar energy collectors are special kind of heat exchangers that transform solar radiation energy to internal energy of the transport medium [15]. The collector is the part of the chimney that produces hot air by the green house effect. It has a roof made up of plastic film or glass plastic film. The roof material is stretched horizontally two or six meter above the ground (figure 6). The height of the roof increases adjacent to the chimney base, so that the air is diverted to the chimney base with minimum friction loss. This covering admits the short wave solar radiation component and retains long-wave radiation from the heated ground. Thus the ground under the roof heats up and transfers its heat to the air flowing radially above it from the outside to the chimney (figure 7) [16]. The structure of the collector changes to the covering material we used.

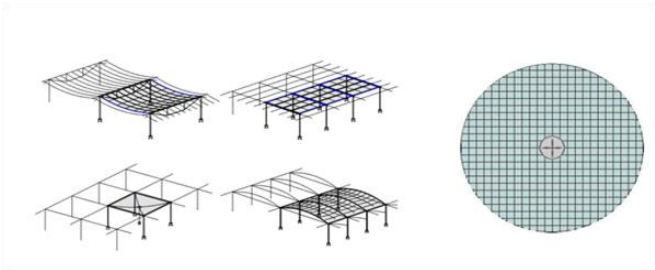

Fig.6. Collector design options.

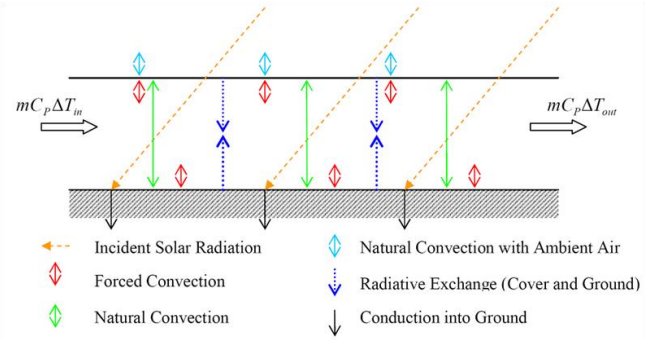

Fig.7. Collector thermal balance scheme.

Significant research effort has been put into the construction, simulation and operation of the solar chimney collector. Two types of collectors were tested by Pasumarthi and Sherif (1997): (1) extending the collector base and (2) introducing an intermediate absorber. The experimental temperatures reported are higher than the theoretically predicted temperatures. The authors explain that one of the reasons for this behavior is the fact that the experimental temperatures reported are the maximum temperatures attained inside the chimney, whereas the theoretical model predicts the bulk air temperature [18]. An analytical model has been presented by Schlaich (1995). Early numerical models have been presented by Kröger and Buys (1999), Gannon and Von Backström (2000), Hedderwick (2001) and Beyers et al. (2002) [19]. Kröger and Buys (1999) present work in their paper specific to the solar chimney collector [20].Kröger and Buys (2001) present a detailed plant analysis also with a transient collector to predict the maximum powers for a one year operational cycle [20]. In Lombaard et al (2002) investigation, the temperatures of the insulated collector plate and glass cover of an horizontal solar collector were measured and compared to theoretically predicted values for different ambient conditions. By ernploying an appropriate equation for the prediction of the heat transfer between the cover and the natural environment, good agreement was obtained between the theoretically predicted and experimentally measured values [21]. M. O. Hamdan (2004) presented an analytical model to predict the performance of a solar chimney power plant. The turbine head have a very strong effect on the second-law efficiency and total harvested power [22]. In 2005, Canadian E. Bilgen and J. Rheault (figure 8) proposed the construction of the solar collector in a sloppy and tapered (with high altitude) section. This idea is of course a brilliant and new idea because the angle of inclination would aid in providing sufficient and effective area of the collector to receive solar radiation, thereby improving the solar collector efficiency. And improving solar collector efficiency would increase the amount of useful heat needed to warm up the cold air [23].

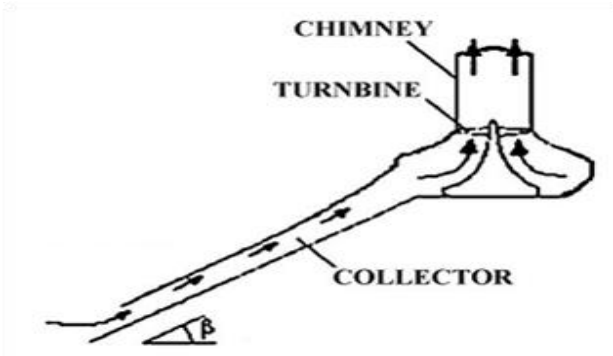

Fig.8. Bilgen and Rheault model [23].

Pretorius and Kroger (2006) evaluated the influence of a developed convective heat transfer equation, more accurate turbine inlet loss coefficient, quality collector roof glass, and various types of soil on the performance of a large scale solar chimney power plant [24]. Various collector types using dry and humid air have been analyzed by N. Ninic (2006) [25]. More recently, a mathematical model for the sloped solar chimney power plant is proposed. The model includes aflow detail inside a collector and the interactive mechanisms between the collector, turbine and chimney [26].

Bernardes et al. developed a comprehensive mathematical model to analyze large scale solar chimney power plant system with a double and single collector canopy with an energy storage layer and turbine performance being considered, comparing simulation predictions to experimental results from the prototype plant at Manzanares, and evaluated the operational control strategies applicable to SUPPS [27,28,29].

Bonnelle (2003) suggests using a collector with a nervelike structure (figure 9), leading to a partial separation of the main functions of the collector, which are (1) collecting heat and (2) transporting hot air to the tower. But, it is still to be proven if such a departure from the standard configuration with a simple glass roof would really improve the collector performance [19, 30].

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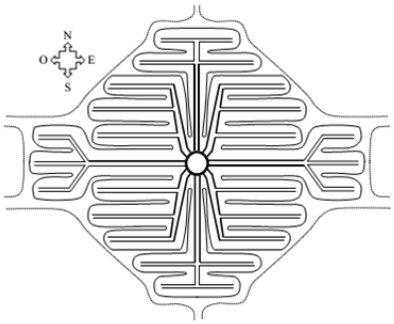

Fig. 9. Bonnelle's solar collector configuration [30].

B. Chimney

Chimney or tower tube; is the main characteristic of the solar chimney station. The tower, which acts like a large chimney, is located at the center of the greenhouse canopy and is the thermal engine for the technology. The tower creates a temperature differential between the cool air at the top and the heated air at the bottom. This creates the chimney effect, which sucks air from the bottom of the tower out of the top. The chimney of the plant is extremely high and will need a stable base while still allowing free flow of air through the turbine. It would also be advantageous to have the turbine as low as possible in the chimney to make its construction simpler [20].

There are various different methods for constructing such a tower: free-standing reinforced concrete tubes, steel sheet tubes supported by guy wires, or cable-net construction with a cladding of sheet metal or membranes (figures 10-11) [31]. The design procedures for such structures are all well established and have already been utilized for cooling towers; thus, no new developments are required. Detailed static and structural-mechanical investigations have shown that it is expedient to stiffen the tower in several stages, so that a relatively thin wall material will suffice. Our solution is to use bundles of strands in the form of "flat"spoked wheels which span the cross-sectional area of the tower. This is perhaps the only real structural novelty in these towers as compared to existing structures.

Schlaich (1994) suggested the reinforced concrete as a building material structure towers high. Studies have shown that practically this method of construction is the alternative most sustainable and cost-effective [16, 32, 33]. Such towers can also be constructed using other technologies including: guyed steel towers which frame is covered with nets of steel cables, membranes or trapezoidal metal films (1994). The maximum height for solar chimney is 1000 m. To support high chimney structure and gigantic solar, compression ring stiffeners are installed with a vertical spacing [34].

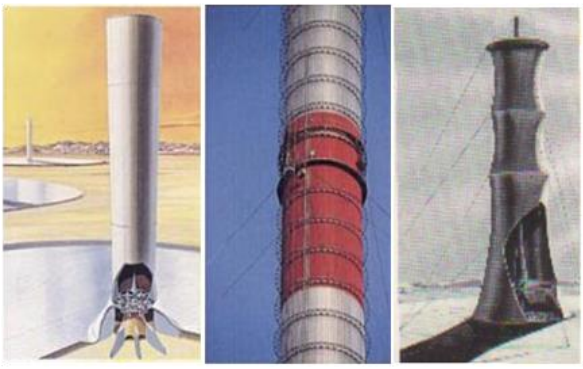

Fig. 10. Différentes technologies de cheminées [16].

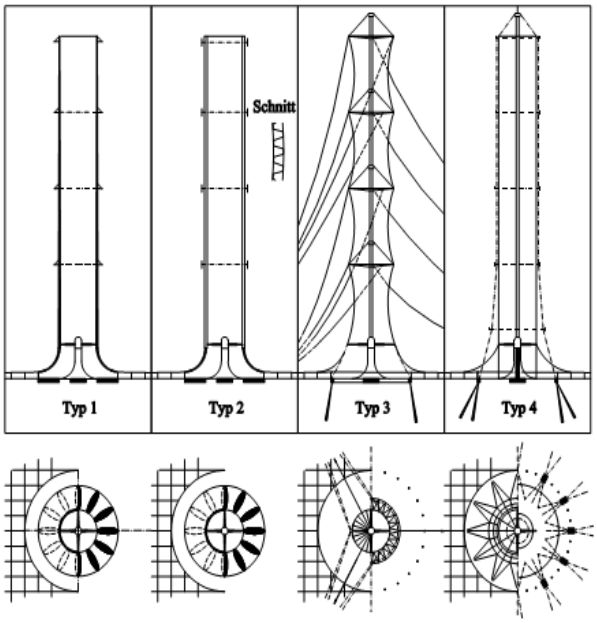

Fig.11. Chimney construction shapes (Bernardes, 2004) [35].

C. Turbines

The turbine of the solar chimney is an important component of the plant as it extracts the energy from the air and transmits it to the generator. It has significant influence on the plant as the turbine pressure drop and plant mass flow rate are coupled. The specifications for solar chimney turbines are in many aspects similar to those ones for large wind turbines. They both convert large amounts of energy in the air flow to electrical energy and feed this into a grid. But there are also various important differences. The following characteristic are typical for solar chimney turbines in contrast to wind turbines [13].

In solar chimneys power plant the turbines are ducted, and their maximum theoretically achievable total-to-total efficiency is therefore 100% the Betz-limit, which is applicable to ducted ones. The direction of the oncoming air flow is known and remains constant. The turbines are protected from harsh weather conditions but have to cope with higher temperatures. The large volumes of collector and chimney act as a buffer preventing large fluctuations in air flow speed, i.e. dynamic loads on the turbine blades and all the other rotating components are comparably low. Furthermore, the turbine pressure drop in SCCPs is about 10 times bigger than in wind turbines [13].

Various turbine layouts and configurations have been proposed for solar chimneys power conversion unit (PCU) (figure 12). A single vertical axis turbine without inlet guide vanes was used in the pilot plant in Manzanares [36]. Configurations with multiple vertical axis turbines has been proposed as well [37], and so have turbine layouts consisting of one pair of counter-rotating rotors, either with or without inlet guide vanes [38]. The air circulation inside the plant, the pressure drop and the flow rate can be adjusted by varying the pitch angle of the blades of the turbine [36]. In order to predict solar chimney conversion unit performance various mathematical models have been developed. The following literature survey focuses on the solar chimney turbines. Many studies were conducted to evaluate the pressure drop across the turbine as a part of the total available pressure difference in the system:

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Haaf et al. (1983), Mullet (1987), Schlaich (1995), Gannon and Von Backström (2000), Bernardes et al. (2003) [20]. Gannon (2002) and Gannon & Von Backström (2003) investigated the performance of solar tower power plant turbines. Turbine design and layout suggestions are made, while an experimental model is used to predict turbine performance and efficiency [39,40]. Later, the same authors (2004) have developed analytical equations in terms of turbine flow and load coefficient and degree of reaction, to express the influence of each coefficient on turbine efficiency. The objective of this work was to predict solar chimney turbine efficiency and operating characteristics to help in solar chimney power plant design optimization [41]. Liu et al. (2005) [32] carried out a numerical simulation for the MW-graded solar chimney power plant, presenting the influences of pressure drop across the turbine on the draft and the power output of the system.

The turbine considered in this study is of the axial type, with radial inflow inlet guide vanes (stator blades) (figure 13) [41].Von Backström et al. (2006) developed two analyses for finding the optimal ratio of turbine pressure drop to available pressure drop in a solar chimney power plant for maximum fluid power. The objective of the study was to investigate analytically the validity and applicability of the assumption that, for maximum fluid power, the optimum ratio of turbine pressure drop to pressure potential (available system pressure difference) is 2/3 [42].

To determine preliminary design parameters, and operating conditions of solar chimney turbines, two counter-rotating turbines, one with inlet guide vanes, the other without, are compared to a single-runner system. The design and off-design performances are weighed against in three different solar chimney plant sizes. In this study Denantes and Bilgen (2006) have concluded that the counter-rotating turbines without guide vanes have lower design efficiency and a higher off-design performance than a single-runner turbine [38].

The technical possibility of utilizing the total operating potential was suggested—partly for generation of the turbine work, and partly for the maintenance of the GVC air flow structure above the ground level. Basic assumptions preceding GVC physical modeling were provided. A significant analogy exists between GVC-flow structures and natural tornados thereby playing the role of an almost experimental confirmation that the proposed GVC structure is technically achievable (2006) [25].

Von Backstörm and Fluri (2007) conducted a study and developed two analyses for finding the optimal ratio of turbine pressure drop to available pressure drop in a solar chimney power plant for maximum fluid power [43]. Nizetic et al (2010) developed a simplified analytical approach for evaluating the factor of turbine pressure drop in solar chimney power plants. This factor (or pressure drop ratio in turbines, according to the total pressure drop in the chimney) is important because it is related to the output power. The determined factor (or ratio) values of the turbine pressure drop are found to be within a value range consistent with other studies. It was concluded that for solar chimney power plants, turbine pressure drop factors are in the range of 0.8–0.9. This simplified analytical approach is useful for preliminary analysis and fast evaluation of the potential of solar chimney power plants [44].

The relationships between the turbine extraction power, the temperature rise across the turbine, the velocity and the mass flow rate are presented in the work of Koonsrisuk (2012) [26].

D. Turbine coupling

Using the Spanish prototype as a practical example, Tingzhen et al (2008) carried out a numerical simulation of a solar chimney power plant system coupled with a 3 blade turbine. This study showed that the average velocity of the chimney outlet and the mass flow rate decrease with the increase of turbine rotational speed. The authors concluded that the average temperature of the chimney outlet and the turbine pressure drop inversely, while the maximum available energy, power output and efficiency of the turbine each has a peak value [45]. Koonsrisuk et al. (2010) conducted a study in which the collector, chimney and turbine are modeled together theoretically, and iteration techniques were then carried out to solve the mathematical model developed. It was developed to estimate power output of solar chimneys as well as to examine the effect of solar heat flux and structural dimensions on the power output. Results from the mathematical model were validated by measurements from the physical plant actually built. The results show that the plant size, the factor of pressure drop at the turbine and the solar heat flux are the important parameters for the performance enhancement [46].

3-D Numerical simulation of the SUPPS couple with turbine conducted by Ming et al. [47] indicated that it is a little difficult to simulate the turbine region and much more meshes are needed to accurately describe flow, heat transfer and output power performances of the system. It was concluded that it is impossible to realize the simulation procedure simultaneously including regions of the solar chimney power plant system, the ambience and the 3-D turbine due to the limitation of grids number. The research work conducted by Pastohr et al. [48] indicated years ago that it is also an efficient way to realize the object by simplifying the 3-D turbine to be a 2-D reversed fan with pressure drop across it being pre-set. This method was also verified by Xu et al. [49] and Ming et al.[50] and was proven to be effective to alleviate the mesh pressure by 3-D turbine region without significantly total performance of solar chimney power plant. Ming et al. conducted a study considering the turbine as a reversed fan with pressure drop across it being pre-set although 3-D model for the SUPPS and the ambience is selected.

To simulate different output power of the turbine, the authors assign the pressure drop a group of values ranging from 0 to 200 Pa at an interval of 20 Pa [51].

A numerical simulation method for the solar chimney power plant system was conducted by Al-Dabbas (2011). The results of comparison between the simulated model and the Spanish prototype with a 3-blade turbine show that with the increase in the turbine rotational speed, the average velocity of the chimney outlet and the system mass flow rate decrease, the average temperature of the chimney outlet and the turbine pressure drop inversely, while the maximum available energy, power output, and efficiency of the turbine each has a peak value [52].

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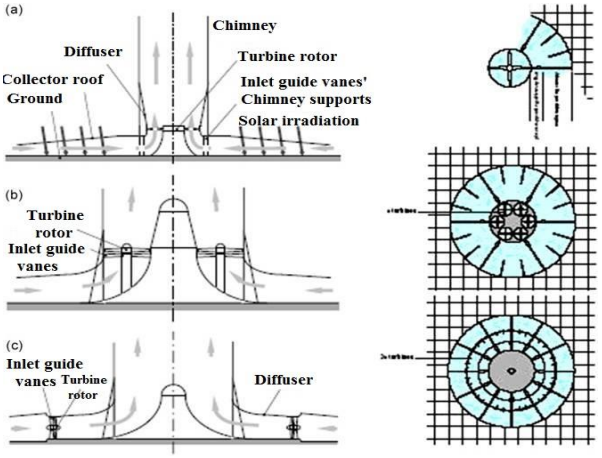

Fig. 12.Vertical view and top view of three turbine configurations: (a) single vertical axis type; (b) multiple vertical axis type; (c) multiple horizontal axis type [53].

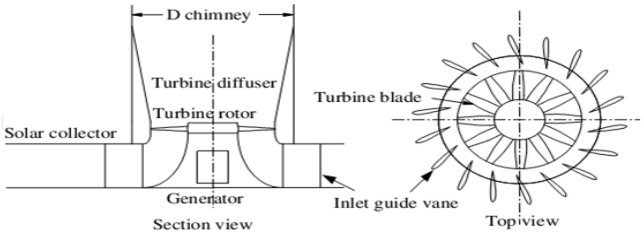

Fig. 13.solar chimney turbine layout [41].

E. Energy storage in the collector

The ground under the collector roof behaves as a storage medium, and can even heat up the air for a significant time after sunset. The efficiency of the solar chimney power plant is below 2% and depends mainly on the height of the tower. As a result, these power plants can only be constructed on land that is very cheap or free. Such areas are usually situated in desert regions. However, this approach is not without other uses, as the outer area under the collector roof can also be utilized as a greenhouse for agricultural purposes [116].

Water filled black tubes are laid down side by side on the black sheeted or sprayed soil under the glass roof collector (Fig. 14). They are filled with water once and remain closed thereafter, so that no evaporation can take place. The volume of water in the tubes is selected to correspond to a water layer with a depth of 5 to 20 cm depending on the desired power output.

Since the heat transfer between black tubes and water is much larger than that between the black sheet and the soil, even at low water flow speed in the tubes, and since the heat capacity of water (4.2 kJ/kg) is much higher than that of soil (0.75 - 0.85 kJ/kg) the water inside the tubes stores a part of the solar heat and releases it during the night, when the air in the collector cools down [54].

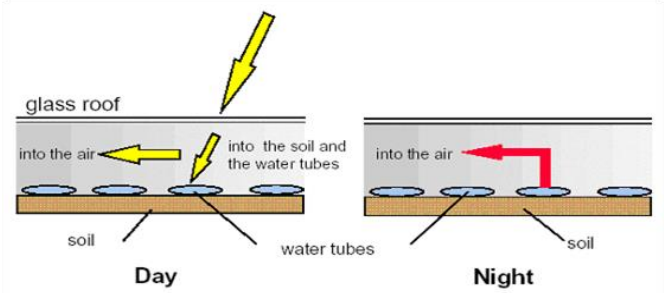

Fig.14. Principle of heat storage underneath the roof using water-filled black tubes [55].

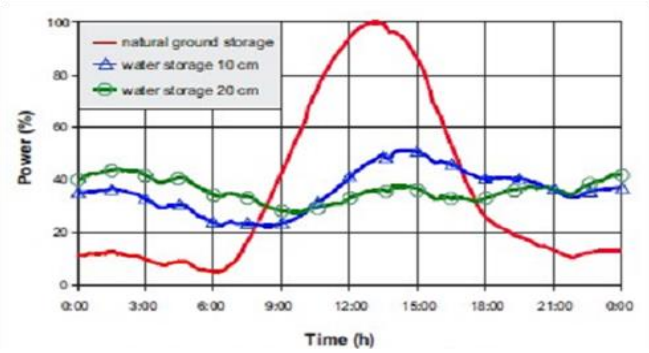

Fig.15. Effect of heat storage underneath the collector roof using water-filled black tubes. Simulation results from (Kreetz,1997) [16].

Kreetz (1997), also furnished with ground water storage systems of solar chimney examined the effect of the power of time, depending (Bernardes, 2004) [35].His calculations showed the possibility of a continuous day and night operation of the solar chimney (figure 15) [29]. Hedderwick [56] and Pretorius et al. (2004) [39] studied and discussed the temperature distributions in the ground below the collector are also presented and discussed. It is thus found that the ground plays an important role in the energy consumption. Pretorius et al. compared the power outputs of six different ground types: sandstone, granite, limestone, and sand, wet soil and water. They found that the SCPPs employing the wet soil and the sand have the lowest and highest power outputs respectively, and different materials lead to varying power outputs during the daytime and at night. Pretorius also concluded that increased ground absorptivity holds positive effects on annual solar chimney power output [17]. Hammadi (2008) have developed a mathematical model for a solar updraft tower with water storage system. This study studied the effect of thermal storage system on the power production of the plant. the obtained results showed that The thickness of the water storage layer is shifted the peak value of the output power far away from mid-day and more smoothing the output curve [57]. Ming et al (2009) analyzed the characteristics of heat transfer and air flow in the solar chimney power plant system with energy storage layer. Different mathematical models for the energy storage layer have been developed, and the effect of solar radiation on the heat storage characteristic of the energy storage layer has been analyzed. Simulation results show that the heat storage ratio of the energy storage layer decreases firstly and then increases with the solar radiation increasing from 200 W/m2 to 800W/m2 and that the average temperature of the chimney outlet and the energy storage layer may increase significantly with the increase of the solar radiation [58]. An experimental study was conducted in Baghdad by Chaichan focusing on chimney's basements kind effect on collected air temperatures. The objective of this study was to examine the effect of basement types on the air temperatures of a prototype solar chimney designed and constructed for this purpose. Three basements were used: concrete, black concrete and black pebbles basements. The results show that the highest temperature difference reached was with the pebble ground. The effects of storage parameter, such as the solar radiation, the ambient temperature, and the heat storage capacity for ground materials on the power plant operation time were also investigated [59].

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To analyze the performance of a solar chimney with energy storage layer Zheng et al (2010) have carried out a numerical study. The response of different energy storage materials to the solar radiation and their effect on the power output were analyzed. This study has shown that soil and gravel could be used as energy storage material for solar chimney system [60].

Ming et al performed unsteady numerical simulations to analyze the characteristics of heat transfer and air flow in the solar chimney power plant system with energy storage layer. The authors established mathematical models of the different parts of the system. They have studied the effect of solar radiation on the heat storage characteristics of the energy storage layer. The numerical simulations showed that it is beneficial for the utilization of soil, with comparatively higher heat capacity, as the material of energy storage layer, which could effectively modulate the temperature and power output difference of the solar chimney power plant between the daytime and night. The simulation results showed that the larger the conductivity of the energy storage layer, the lower the surface temperature of the energy storage layer [61].

Fanlong et al (2011) adopted in their research the hybrid energy storage system with water and soil to decrease the fluctuation of solar chimney power generating systems. The authors established mathematical models of fluid flow, heat transfer and power output features of solar chimney including an energy storage layer. Also the influence of the material and depth of energy storage medium upon power output has been analyzed. The simulation results demonstrate that hybrid energy storage system with water and soil can effectively decrease the power output fluctuation [62].

Najmi et al (2012) have chosen Paraffin as the material of energy storage layer. In this study, an unsteady conjugate numerical simulation of the system was done by FLUENT software. The operation condition of the system was simulated when the solar radiation value was changed with time according to the actual situation. Due to the energy storage effect of phase change materials, the system had output power of 1.3W at night. Moreover because of the continuous work of the heat storage layer, in the same condition of solar radiation, the air velocity and maximum output power increased with the system operation days extended [63].

Xu et al. (2011) performed a numerical simulation of a solar chimney with an energy storage layer similar to the Spanish prototype [64]. An experimental investigation of the effect of ground temperature changes on the solar chimney system were carried out by Buğutekin [65].

V. PROJECTS

SCPPs are promising for large-scale utilization of solar energy, and extensive research has been carried out to investigate its huge-potential over the world. Based on an Analysis of the geographical conditions and solar-energy resources in many countries, the feasibility of constructing a solar hot air-flows power generating system was illustrated.

A. Manzanares prototype

Schlaich Bergermann has designed, constructed and operated an experimental plant with a peak output of 50 kW on a site made available by the Spanish utility Union Electrica Fenosa in Manzanares (about 150 km south of Madrid) in 1981/82 (Figure 16), with funds provided by the German Ministry of Research and Technology (BMFT) [66]. The aim of this research project was to verify, through field measurements, the performance projected from calculations based on theory, and to examine the influence of individual components on the plant's output and efficiency under realistic engineering and meteorological conditions. Erection of the plant was completed in 1981, and after a phase of improvements, continuous operation started in 1983 and continued until 1989 [67].

In May, 1982 Spaniards living near the small central town of Manzanares, 150 km south of Madrid, saw a strange giant arising. It was a metal tower nearly 200 m high made of sheet steel rings, surrounded by an array of plastic sheeting 240 m across (see Fig16). The main characteristics of the prototype are illustrated in table I. The developers claim that The Manzanares plant achieved an electricity efficiency of 0.53% but SBP believe that this could be increased to 1.3% in a large 100 MW (e) unit with detail improvements (Schlaich, 1995). The efficiency of these plants increases with size. The capacity factor measured at Manzanares was 10% but it is claimed this would rise to 29% in a 200 MW (e) unit. The Manzanares plant was retrofitted for a test with black plastic containing water mining scrap can be used for this purpose [68]. The SBP technology originally used plastic sheet glazing at Manzanares, but this encountered severe structural instability close to the tower due to induced vortices. Toughened glass is likely to be used for all future plants. Because of size, array-cleaning cost is an important area of concern. However, other maintenance costs associated with this approach seem to be very low [68].

The solar chimney pilot plant in Manzanares, Spain, has demonstrated the technical feasibility of electricity generation with solar chimney power plants. Electrical power output is a function of a global irradiation, but also depends on meteorological and environmental conditions [69]. The pilot project worked for about eight years until the chimney support wires rusted out and the chimney was blown over in a storm, but it did prove that the concept was scientifically sound. To get meaningful amounts of power out of such a system (that is to get megawatts instead of kilowatts) requires construction of a substantially taller chimney. The taller the chimney, the stronger the updraft; the stronger the updraft, the more power you can generate [11].

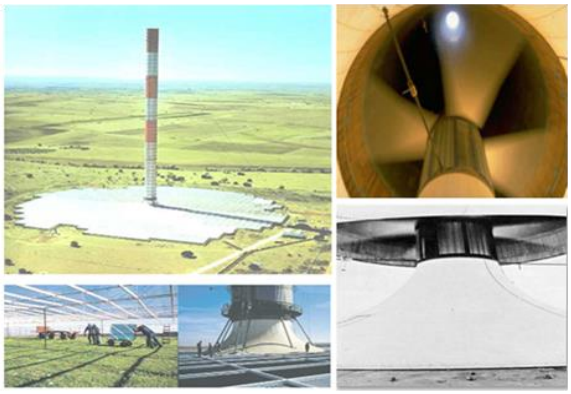

Fig.16.the solar updraft tower in Manzanares, Spain (construction in 1982, SBP) [16, 34].

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Table.I. Data and design values of the pilot plant [16,70].

Parameters		Manzanares prototype
Tower height	(m)	194.6
Tower radius	(m)	5.08
Collector radius	(m)	122
Chimney weight	(kg)	125.10^3
Average height of the collector	(m)	1.85
Number of turbine blades		4
Turbine blade profile		FXW-151
Radius velocity		1 :10
Radius transmission		1 :10
Collector temperature	(°C)	ΔT=20
Nominal output (kW)		50
Glass roof- collecteur area	(m^2)	6000

B. *Enviromission power plant*

In 2001, a company called Enviromission announced that it planned to build a 200 megawatts solar chimney in southwest Australia that could generate 4000 times more power than the Manzanares system. The Australian firm is working with the German consultants Schlaich Bergmann [71]. But to get that kind of power, Enviromission must construct a solar chimney (see figure 17) that's 130 meters in diameter and 1000 meter tall, which is more than 11 times the height of the statue of liberty and nearly twice as tall as Toronto's CN tower. Enviromission would have to break a world record for its solar chimney to become a reality. Also, to create enough warm air to flow through that chimney will require a plastic or glass covered solar collection area of up to 35 square kilometers, roughly equivalent to 5000 NFL football fields. The project is expected to cost nearly $ 1 billion [11].

The 1000 m tower will be built from reinforced concrete and strengthened by horizontal metal supports that can also act as platforms. The air temperature under the collector roof will be around 30°C and the wind speed will be about 32 km/h. Energy will be extracted from this flow using 32 turbines set horizontally in the transition area [72]. The turbines will be purposely built from lightweight alloy materials, with 10 blades coupled to synchronous generators. The turbines will receive air at around 60°C to 70°C [73].

Enviromission has two projects planned for Arizona, in 2011, secured $ 30 million in funding to cover early developments costs. Solar chimneys are also being considered in other parts of the world. Projects are on the drawing board in the European Union and Africa, including a solar chimney in Namibia dubbed Green tower that would reach 1.5 kilometers into the sky and require a solar collecting greenhouse covering 37 square kilometers. None of these commercial scale projects have reached construction phase, and there is no certainty they will [11].

Fig.17. Enviromission power plant scheme.

C. *Chinese prototype*

The region of Jinsha Bay Wuhai in Inner Mongolia (China) has built an experimental prototype solar chimney of 200 kW. The total planned capacity until December 2013 this project is 27.5 MW, representing a total of 2.78 million m2 of desert occupied by greenhouses as a collector and a total investment of 1.38 billion yuan. The construction of the Chinese prototype was performed in three phases:

-the first phase of the project has already been completed between May 2009 and December 2010 and helped build a prototype solar chimney 200 kW demonstration occupies 40,000 m2 of desert tower or chimney 53 m high and 18m in diameter, representing an expenditure of 1 million yuan;

-the second phase of the project has just started in February 2011 and lasted until December 2011 to complete the construction of a power plant based on 2.2 MW solar chimney. This system demonstration will occupy 220,000 m2 of desert and the planned investment is 110 million yuan;

-the third phase of the project will be carried out between January 2012 and December 2013, to allow the construction of a solar chimney power plant of 25.1 MW, with a greenhouse collector occupying a desert region of 2.51 million m2, the investment will be 1.26 billion yuan (1.2 billion yuan Chinese) [74].

D. *Other solar updraft towers*

Jinshawan Updraft Tower

In December 2010, a solar updraft tower in Jinshawan in Inner Mongolia, China started operation, producing 200-kilowatts of electric power. The 1.38 billion RMB (USD 208 million) project was started in May 2009 and its aim is to build a facility covering 277 hectares and producing 27.5 MW by 2013. The greenhouses will also improve the climate by covering moving sand, restraining sandstorms [75].

Ciudad Real Torre solar

There is a proposal to construct a solar updraft tower in Ciudad Real, Spain, entitled Ciudad Real Torre Solar. If built, it would be the first of its kind in the European Union and would stand 750 meters tall – nearly twice as tall as the current tallest structure in the EU, the Belmont TV Mast – covering an area of 350 hectares (about 865 acres). It is expected to put out 40 MW of electricity [75].

Bostwana Test facility

Based on the need for plans for long-term energy strategies, Botswana's Ministry of Science and Technology designed and built a small-scale solar chimney system for research. This experiment ran from 7 October to 22 November 2005.

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It had an inside diameter of 2 m and a height of 22m and was manufactured from glass-reinforced polyester material, with a collection base area of approximately 160 m2. The roof was made of a 5 mm thick clear glass that was supported by a steel framework [75].

Namibian proposal

In mid 2008, the Namibian government approved a proposal for the construction of a 400 MW solar chimney called the 'Greentower'. The tower is planned to be 1.5 km tall and 280 m in diameter, and the base will consist of a 37 km2 greenhouse in which cash crops can be grown [75].

Turkish model

A model solar updraft tower was constructed in Turkey as a civil engineering project. Functionality and outcomes are obscure. Mountainside Solar Draft Tower - In 1926 Prof Engineer Bernard Dubos proposed to the French Academy of Sciences the construction of a Solar Aero-Electric Power Plant in North Africa with its solar chimney on the slope of a large mountain. A mountainside updraft tower can also function as a vertical greenhouse [75].

Arctic Solar draft tower

A Solar updraft power plant located at high latitudes such as in Canada, could produce up to 85 per cent of the output of a similar plant located closer to the equator, but only if the collection area is sloped significantly southward. The sloped collector field is built at suitable mountain hills, which also functions as a chimney. Then a short vertical chimney is added to install the vertical axis air turbine. The results showed that solar chimney power plants at high latitudes may have satisfactory thermal performance [75].

E. Experimental prototypes

For different regions, configuration sizes of SCPPs are different because of various meteorological and geographic conditions. In 1997, a system was established by Pasurmarthi Sheriff and Florida (see Figure 18-a). They present the construction and testing of a small scale chimney. The testing focused on the heat transfer performance of the collector and methods to try and improve this [20]. The diameter of 9.15 m is equal to the tower height is equal to 7.92 and its diameter gradually decreases from 2.44 m to 0.61 m base to the summit. Absorber aluminum plate was attached to the floor under the roof of the collector [34]. A pilot experimental solar chimney power setup composed of 5 m radius air collector and a chimney 8 m in height has been built in HUST, China. The size of the opening at the periphery of the collector was chosen as 0.05 m, and was constructed to be readily adjustable.

Standard PVC drain-pipes 0.3 m in diameter were used as a chimney. Because of construction costs, the actual slope angle of the collector was chosen as 8°, and the height from the collector outlet to the ground level was therefore 0.8m. The pilot solar chimney power setup was designed and built in December, 2002 in order to investigate the temperature field as well as to examine the effect of time of day on the temperature field (fig 18-b) [76]. The collector roof and the SC were made of glass 4.8 mm in thickness and PVC, respectively [77]. A heat insulator was used to pack the steel-frame structure of the collector to avoid diffusing heat through it. The water in the pipes (6 cm in diameter) was selected as the storing body. One centimeter thick composite layer bed with asphalt and black gravel was applied as the top layer to absorb solar energy, and then heat was transferred from the top layer to water pipes. A multiple-blade designed on the operating principle of turbine blade was installed at the base of the chimney [76].

A pilot solar chimney was also built on the campus of Suleyman Demirel University-RACRER (Research and Application Center for Renewable Energy Resources), in Isparta, Turkey, which had 15 m high, 1.2 m in diameter and a glass covered collector 16 m in diameter (fig 18- c). After the experimental studies, the system is modeled theoretically with depending on the design. Then, this model constituted the basis for developed computer program and performance parameters of the system are obtained [78].the main dimensions of constructed prototype are illustrated in table II.

Table.II. Characteristics of the prototype solar chimney (Üçgül, 2005).

parameters	symbol	value
Chimney height (m)	H_{gb}	15
Collector diameter (m)	D	16
Greenhouse area (m^2)	A_s	200.96
Chimney (m^2)	A_b	1.19
Inlet environmental field (m^2)	A_g	31.148

Based on the need for plans for long-term energy strategies, Botswana's Ministry of Science and Technology designed and built a pilot SC power setup for research. SC was manufactured from glass reinforced polyester material, which had an inner diameter of 2 m and a height of 22 m. The collector roof was made of a 5 mm thick clear glass supported by a steel framework. The collection area reached at approximately 160 m2. The absorber under the roof was made of two layers of compacted soil approximately 10 mm thick and a layer of crushed stones. The layer of crushed stones was spread on the top surface of the compacted soil layer [79]. Together with their supervisors Prof. Rainer Gumpp (Design and Construction of Supporting Structures) and Prof. Dr.-Ing Jürgen Ruth (Structural Engineering), an international team of three Architecture and five Civil Engineering students designed and built the solar chimney in one semester as part of their interdisciplinary Archineering master's degree programme. The prototype was installed in Bauhaus University in Weimar, Germany (fig 19-d).

The system is constructed of 420 m2 plastic foil at its base. The warm air travels up the 12-metre chimney – an efficient lattice construction with a red insulating tarpaulin – and creates an updraft. During its phase of operation in summer 2008, the electricity was stored in batteries which powered energy-efficient LED lights for illuminating the construction at night [80]. A practical prototype model of the solar chimney power plant was designed and constructed to investigate the influence of basement kinds on chimney's air temperatures, in the region of Baghdad city- Iraq. The prototype is composed of a circular transparent roof (6 meters diameter) opened at the periphery (2 cm high from ground). In the middle of the roof there was a vertical tower (4 meters tall and 20cm diameter) with large air inlets at its base (10 cm high from the ground) . The study was conducted in Baghdad from August to November 2010 (fig 18-e) [81]. A physical prototype was built in Belo

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Horizonte (Brazil) for the validation of the mathematical model and the numerical methodology used. A tower of 12.3 m in height was constructed with sheets of wood and covered by fiberglass at a diameter of 1.0 m. The cover was made of a plastic thermo-diffuser film. The cover, with a diameter of 25 m, was set 0.5 m above the ground level, using a metallic structure. The absorber ground was built in concrete and painted in black opaque (Fig. 19-f). Analysis showed that the height and diameter of the tower are the most important physical variables for solar chimney design [82]. A solar chimney system was established in Adıyaman University campus (fig. 18-g) area designing a special layered soil (27 m diameter and 0.5 m deep drop -circular hole, while the aluminum foil, glass wool, sand, gravel, broken glass trotters windscreen and its top surface, asphalt) on the 0.004 m thick glass laying the panels, 17 m height of 0.8 m in diameter chimney and a height adjustable air inlet collector (periphery) from 0.05 to 0.35 m to investigate the effect of environmental temperature, chimney height, the collector diameter, the value of solar radiation etc on the performance or effectiveness of Solar Chimney (SCS) [83].

In order to evaluate the solar chimney model, a prototype is constructed in AlAin, United Arab Emirates (UAE) as shown in Fig. (18-h) which consists of a 10m x10m collector and an 8.25 m tall chimney. A steel pipe with diameter of 24 cm and height of 8.25 m is used to construct the solar chimney tower which is supported by steel beams. The collector is constructed using steel beams with steel wired network use to support a semi-clear plastic cover. The collector surface is designed with inclination to allow water drainage in the event of rain with collector height from the ground of 0.5m near the collector edge and 0.75m at the collector center [84].The solar chimney data are collected over the period of three days on December 2011. The purpose of this work is to evaluate experimentally the performance of solar chimney and compare it with the mathematical thermal model prediction. The study report the effect of internal collector dynamic temperature, the amount of solar energy trapped within the collector, and expected wind draft inside the chimney.

A solar chimney has been built in Kerman (Kerman city-Iran). The chimney has 60 m height and 3 m diameter. The collector of this prototype is 40 m×40 m square. This work has presented an economic analysis of a solar chimney prototype. It has proposed suggestions to maximize usage of solar energy and calculated the maximum power of the unit (fig 18-i) [85]. The figure (18-j) shows the first Mutah University (Jordan) pilot solar chimney. This prototype was built in 2009. The physical properties, main dimensions and operating parameters are illustrated in table 3 [86].

For performing the experimental works and temperature measuring, a solar chimney in pilot scale was built in University of Zanjan, Iran, in 2010 (fig 18-k). The chimney height is 12 m and the collector has 10 m diameter. The collector slope angle must have been designed so that it could absorb the maximum solar radiation. Zanjan town has geographical length and width of 48.45 and 36.68, respectively. So, for absorbing the most heat by collector, the collector exit must have a height of 5tan π/6. Due to design limitations, the exit was built with 1 m height and the collector inlet was built with 15 cm height.

Because of heat resistance and low price of polyethylene (PE), a 12 m PE pipe with diameter of 25 cm was used for making the chimney. The friction is low in the pipe, due to low diameter and low height. For strengthening the structure, 48 pieces of 4*4 steel profiles were used in the collector and the collector bases were put inside concrete. For preparing a proper green house effect, polycarbonate (PC) sheets were applied for making the collector sheets. Polycarbonate sheets are mechanically strong, transparent, tough, heat resistant, and fairly UV resistant. For preventing heat loss and increasing the green house effect, two-layered PC sheets were selected. Since black material can be more thermally black [28], the ground under collector was totally covered by black films of polyethylene [87].

Table.III. physical properties, main dimensions, and operating parameters of the pilot solar chimney in Mutah University.

$R_{coll} = 3.4$ m $H = 4$ m Main collector roof high = 1 m $V_{in} = 2$ m/s $r_{out} = 1.0$ kg/m^3 $g_4 = 0.0065$ K/m $h_{coll} = 0.6$ $T_{in} = 305$ K	$R_{cin} = 0.285$ m $R_{c\,out} = 0.29$ m $h_{in} = 7.5$ W/m^{2}C $h_{out} = 15$ W/m^{2}C The cross-section area of the chimney = 0.2642 m^2 The area of the solar collector $A_{coll} = 36$ m^2 $V_{out} = 0.5$ m/s	$r_{in} = 1.0$ kg/m^3 $G = 517$ W/m^2 $c_p = 1.0090$ kJ/kgC $T_{out} = 300$ K $k_{steel} = 59$ W/m^{2}C $L_{chimney} = 4$ m $A_{in} = 7.16283$ m^2 $A_{out} = 7.2885$ m^2

The first experimental solar chimney in Tunisia was installed by the Higher Institute of Science and Energy Technology of Gafsa (2009). The outer cover of the collector was constructed in plastic (Plexiglas). The inner cover was in glass. The distance between Plexiglas and glass is chosen small enough (less than 2.5 cm) in order to neglect the thermal convection between the two covers. To ensure the strength, we must put 8 plates in the collector diametrically apart 5.9 m. part of the collector is formed by three circular rings of equal distance to 2.5 m. The angle of inclination of the collector relative to the ground should be chosen to maximize absorption of solar radiation when the angle of the collector is equal to the local latitude Gafsa 34°,25 north. To minimize the cost of construction and ease of maintenance of the prototype, the solar chimney parameters are chosen as presented in table IV [88].

The construction of the chimney required the use of 10 iron cylindrical barrels with a height of 1.6 m and a diameter of 0.2 m. These barrels were butt-welded. To maintain the chimney, tow collars were used at 6.5 and 12.5 m from the ground. For each of them, steel cables were used. The turbine will be installed at a height not exceeding 0.55 m. the platform of the turbine will be installed downwardly. The blades of the turbine are made of aluminum. The diameter of the turbine (vertical axis) chosen to prevent air leakage was equal to 0.36 m (fig 18-l) [88].

The theoretical and numerical research Koonsrisuk and Chitsomboon led to the establishment of four small-scale experimental plants on a site at Suranaree University of Technology (Nakhon Ratchasima, Thailand) (see figure 19). The experimental system was designed and constructed and was used to study the temperature and velocity profiles within the solar chimney. A numerical model for each plant was also developed and compared the simulated results with experimental observations [89].

Experimental Set 1 has the roof with adjustable inlet height and constant-diameter chimney. Experimental Set 2 has the roof with adjustable inlet height and divergent-top chimney. Experimental.

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Set 3 has the collector with a novel roof shape designed by the researcher and a constant-diameter chimney. Experimental Set 4 is the half-size model of Experimental Set 1 (see table V).

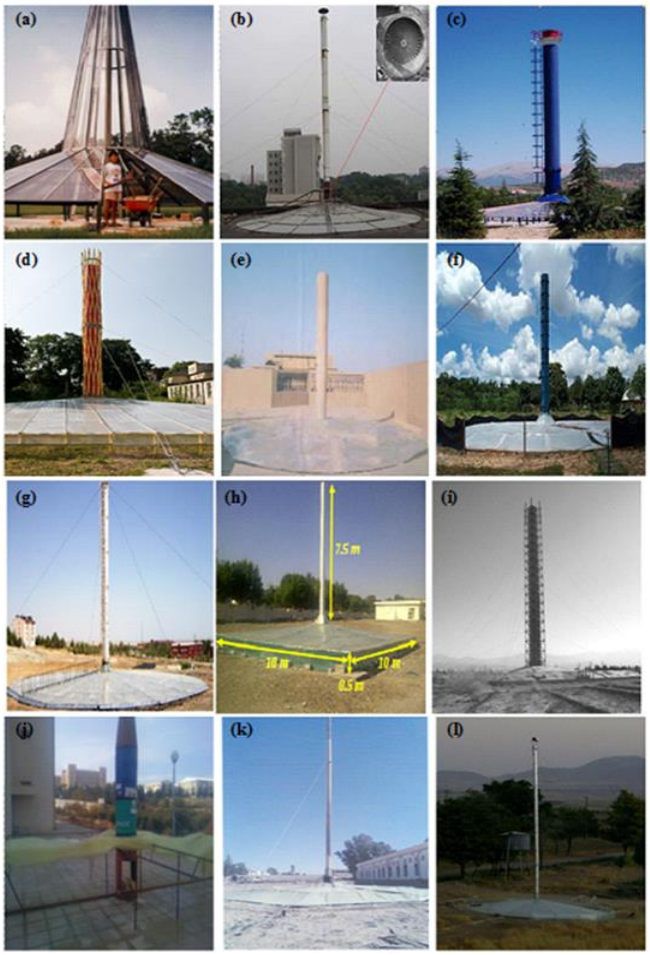

Fig.18.solar chimney experimental prototypes.

Table .IV. Main dimensions of the Tunisian prototype.

parameters	value
Inclination angle (°)	1.5
Collector diameter (m)	15
Collector height (m)	0.5
Chimney diameter (m)	0.4
Chimney height (m)	16

Table.V. Specification of the experimental sets.

Chimney height (m)	Roof description	Roof height above the ground	Note
8	Octagonal shape; fully opened at	Selectable at 0.06; 0.08; 0.13; 0.25 and	Constant diameter chimney
8	Octagonal shape; fully opened at	Selectable at 0.06; 0.08; 0.13; 0.25 and	The same size as model 1;divergent top
8	squared shape; partially	Fixed at 0.5 m	The same roof area as model 1;
4	Octagonal shape; fully opened at	Selectable at 0.04; 0.05; 0.07; 0.15 and	Half size of model 1

Fig.19. photos of experimental sets.

VI. NUMERICAL STUDIES

Computational fluid dynamics (CFD) has become an indispensable tool for engineers. CFD simulations provide insight into the details of how products and processes work, and allow new products to be evaluated in the computer, even before prototypes have been built. It is also successfully used for problem shooting and optimization. The turnover time for a CFD analysis is continuously being reduced since computers are becoming ever more powerful and software uses ever more efficient algorithms. Low cost, satisfactory accuracy and short lead times allow CFD to compete with building physical prototypes, i.e. 'virtual prototyping' [83].

There are many commercial programs available, which have become easy to use, and with many default settings, so that even an inexperienced user can obtain reliable results for simple problems. However, most applications require a deeper understanding of fluid dynamics, numerics and modelling. Since no models are universal, CFD engineers have to determine which models are most appropriate to the particular case. Furthermore, this deeper knowledge is required since it gives the skilled engineer the capability to judge the potential lack of accuracy in a CFD analysis. This is important since the analysis results are often used to make decisions about what prototypes and processes to build [83].

Numerical simulations via commercial codes are popular, and greatly facilitate computational study of solar chimney. Many researchers have carried out CFD numerical studies on this new technology. The simulation approaches for the solar chimneys' performance reported in the literature can be classified into categories: ones that use an existing simulation model and ones that are associated with development of a model for prediction of a solar chimney performance [90]. The first known CFD study of (Computational Fluid Dynamics) the convective flow in a SCPP is showed by (Bernardes, et al., 1999). He presented a solution for Navier Stokes and Energy Equations for the natural laminar convection in steady state, predicting its thermo-hydrodynamic behavior. RMValle MFCortez [91] led the first numerical simulation of laminar natural convection in a solar tower.

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For the prediction of thermo-hydrodynamic behavior of the system, the mathematical model (balance equations of momentum and energy) was operated using the finite volume method in generalized coordinates. Then, Pastohr et al. [48] carried out an analysis to improve the description of the operation mode and efficiency of solar chimney power plant. Authors modeled all system parts (collector, chimney, turbine and ground) numerically based on the Manzanares prototype geometric parameters. The numerical results given by the commercial software FLUENT was compared to those of the analytical model developed. Ming et al. [91] presented the influence of various parameters (solar radiation, collector radius and chimney height) on the relative static pressure, driving force, power output and the system efficiency. Later, the same authors [58] performed numerical simulations to analyze the characteristics of flow and heat transfer system which includes a layer of energy storage. Mathematical models of the collector, the chimney and the storage medium have been established and the effects of different solar radiation on the characteristic of heat storage layer were analyzed. Ming et al. [45] conducted a numerical study of a solar chimney coupled with a 3-blade turbine. They have presented the effect of turbine rotational speed on the power plant outlet parameters. To give a reference to the design of large scale solar chimney, authors have performed a numerical simulation of a MW-grade solar chimney. With the help of the numerical code FLUENT, Huang et al. [92] have used the Spanish prototype as a model to study the effect of solar radiation on various parameters such as upwind velocity, temperature difference between the inlet and outlet of collector and the differential pressure of the collector-chimney transition section. More recently, Ming et al. [93] have performed a study of the fluid flow inside many parts of the solar chimney and established an analysis of the thermodynamic cycle. Zheng et al. [60] have developed a mathematical model to analyze heat and mass transfer in a solar chimney power plant with an energy storage layer. Based on an unsteady numerical simulation, they have studied the effect of some energy storage materials under different solar radiation on the system power output. Chergui et al. [94] have modeled numerically the process of laminar natural convection in a solar chimney. Researchers have focused on heat and airflow transfer inside the system. The resolution was obtained using the formulation in primitive variables (velocity-pressure) with the finite volume method. They analyzed the effect of the geometry and Rayleigh number on the phenomenon. Sangui et al. [95] have performed a numerical analysis of a tow dimensional axisymetric model of solar chimney using two different ways: an iterative technique and the commercial CFD code Fluent. The results obtained were compared with the experimental data of the Spanish prototype. Two-dimensional steady-state numerical simulations on air flow, heat transfer and power output characteristics of a solar chimney power plant model with energy storage layer and turbine similar to the Spanish prototype were carried out by Xu et al. [64].

The study of Hurtado et al. was carried out based on the Manzanares prototype solar chimney power plant. This work analyzes the thermodynamic behavior and the power output of a solar chimney power plant over a daily operation cycle taking into account the soil as a heat storage system, through a numerical modeling under non-steady conditions. The influence of the soil thermal inertia and the effects of soil compaction degree on the output power generation are studied. A sizeable increase of 10% in the output power is obtained when the soil compaction increases [96]. Using a self-developed MATLAB program, Jing-yin et al have evaluated the performance of a solar chimney power plant. The obtained results have been compared with experimental data of the Spanish prototype. A comprehensive theoretical model has been developed by taking account of the detailed thermal equilibrium equations in the collector, the system driving force and the flow losses based on existing experimental data or formulas. The theoretical model has been validated by the experimental data of the Spanish prototype [97].

VII. UNCONVENTIONAL SOLAR CHIMNEYS

Other propositions about unconventional solar chimneys were presented in the literature such as: sloped, floating, geothermal and hybrid cooling tower–solar chimney and chimney solar pond combination.

A. Sloped solar chimney

The first study of a sloped solar chimney was proposed by Bilgen et al. The basic concept explored by this author is to construct a chimney with a collector in a sloppy section [23]. Later, S. V. Panse et al. explored this concept though differently and considered that the inclined face of the mountain itself acts as the chimney as well as the solar energy collector [100,102]. The authors have studied the feasibility of the concept of Inclined Solar Chimney and study the factors affecting its power output. In another study, Zhou et al. suggested that a hole can be excavated at the center of a high rising mountain, which will act as the chimney. The collector area would be spread around the mountain [101]. A sloped solar chimney power plant, which is expected to provide electric power for remote villages in Northwest China, has been designed for Lanzhou City. The designed plant, in which the height and radius of the chimney are 252.2 m and 14 m respectively, the radius and angle of the solar collector are 607.2 m and 31° respectively, is designed to produce 5 MW electric power on a monthly average all year. This kind of solar power plant has a sloped solar collector and a short vertical solar chimney. It is called the sloped solar chimney power plant (SSCPP). Reports of SSCPP are few comparing to the study of the classical solar chimney power systems by F. Cao et al. [99]. More recently, Cao et al work (2013) have compare the performance of a conventional solar chimney power plant (CSCPP) and two sloped solar chimney power plants (SSCPPs) with the collector oriented at 30° and 60°, respectively (figure 20) [98].

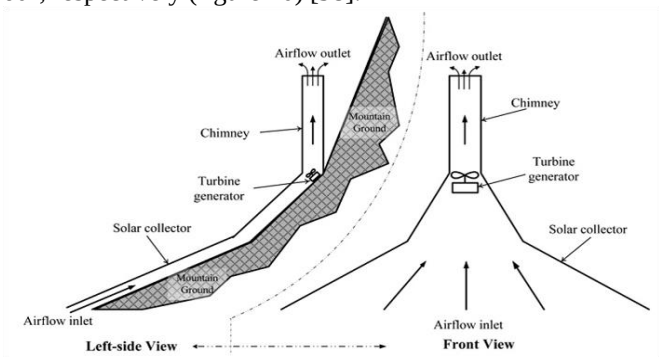

Fig. 21.Schematic of a sloped solar chimney power plant [98].

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B. *Floating solar chimney*

The floating solar chimney technology was presented by Papageorgiou in a series of papers [103-110]. A Floating Solar Chimney (FSC) power plant is made of three basic parts:

- A large solar collector with a transparent roof supported a few meters above the ground, open at its perimeter (the greenhouse).
- A tall lighter than air cylinder in the center of the solar collector (the Floating Solar Chimney)
- A set of air turbines geared to appropriate electric generators placed inside or around the FSC (the turbo-generators) [103].

The chimney in this system is not made of concrete, but of a flexible material and floats on air with the help of a lighter gas like helium. The chimney essentially has a heavy base and the walls are filled with a lighter gas. The support rings allow air to enter and pass through them freely, so that the chimney does not yield under wind pressure [100]. Due to its patented construction the FSC is a free standing lighter construction than air structure and behaves like bending when external winds appear, as shown in the figure 21 and 22.

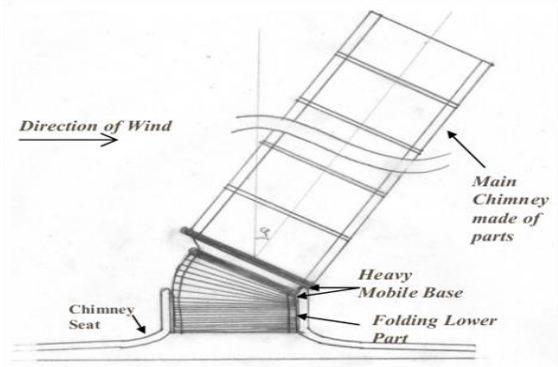

Fig.21.floating solar chimney scheme.

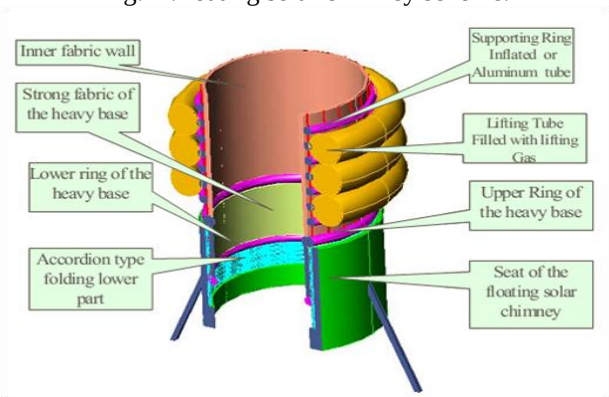

Fig. 22. An indicative presentation of the Floating Solar Chimney.

C. *Geothermal- solar chimney*

In orders to increase the efficiency of the solar chimney power station, some approach were proposed in the litterature such as: a hybrid geothermal solar chimney power plant (figure 23). This novel technology allows the thermal conversion of energy by operating with both solar and low geothermal energy. This proposition allows the generation of electrical energy even when sunlight is not available. Thus, during cloudy days and at night, a full geothermal operation mode or the combination of solar and geothermal can ensure the working of the installation [111].

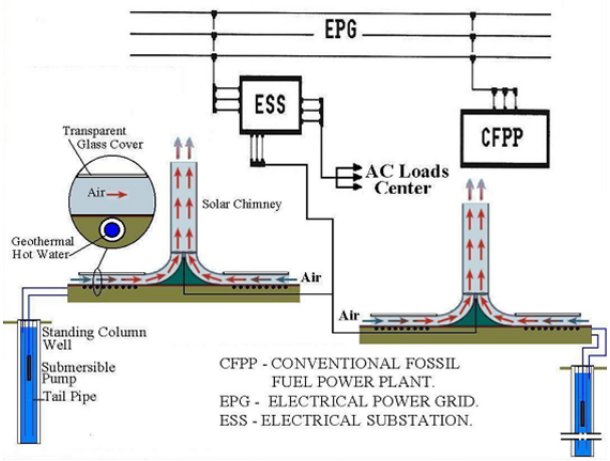

Fig.23. hybrid geothermal solar chimney [111].

D. *Hybrid cooling tower- solar chimney*

Based on the conventionel solar chimney system, Zandian et al. have introduced a new concept capable to produce more electrical energy by recapturing the rejected heat from the condenser supplemented by the solar energy gain from the solar collectors [112].

The working principle of this system is as follow: The ambient cool air enters the system from the open base periphery and passes through the radiators and cools the condenser water within its path. The heated air then passes through the space under the transparent roof and gains more heat from solar radiation. The transparent roof and the ground below it act as a collector and heat up the flowing air more. The buoyant airflows radially towards the center of the system, where some Inlet Guide Vanes (IGVs) direct it through a wind turbine, which is installed at the throat of the chimney. The air drives the turbine in its path and generates electrical power similar to that in solar chimneys [112].

E. *Chimney solar pond combination*

In 2002 a small prototype combining a solar pond with a chimney was constructed at the RMIT Campus in Bundoora (20 km north of Melbourne). The diameter of the chimney was 0.35 m and the height was only 8 m. The tower was constructed from flexible circular ducting as used in domestic heating systems. Since this material is flexible the duct was supported by the structure of a small experimental aero generator which was within a few meters of a small experimental solar pond of approximately 4.2 m diameter and 1.85 m depth (see figure 24) [113].

Later, Akbarzadeh et al. have examined the concept of combining a solar pond with a chimney to produce power in salt affected areas. The authors have proposed tow scenarios to produce electricity by solar pond-chimney combination. In the first one a non-direct contact heat exchanger is utilized, while the unit on the second one uses a direct contact heat exchanger (see figure 25). Heat is removed from the solar pond by extracting hot brine from just below the interface between the gradient layer and the bottom convective zone and pumping it through a water-to-air heat exchanger inside the tower. After delivering its heat, the water is returned to the bottom of the solar pond. Thus the ambient air is heated and as a result the desired draft is created inside the tower. The induced air flow can be utilised by an air turbine to produce power [113].

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Lu Zuo have presented a new solar chimney power system with integration of sea water desalination is introduced for the production of electricity and fresh water [98]. More recently, a concept using solar chimney system to drive both power generation and seawater desalination suitably at a site adjacent to the sea was proposed by Wang et al.[114].

Fig.24.the photograph of the Bundoora prototype.

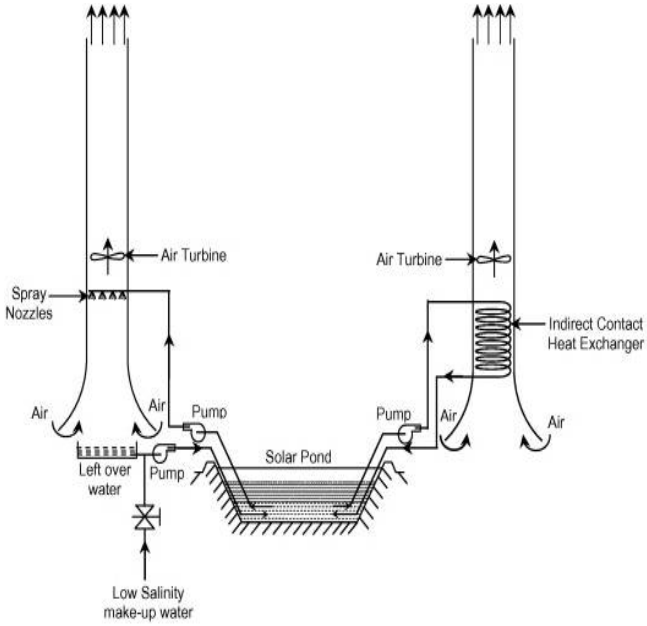

Fig. 25.Concepts for combining a chimney with a solar pond to generate power.

VIII. CHARACTERISTICS OF THE PLANT

Overall, the solar chimney concept has much to offer. It is unique in its ability to convert low grade heat into usable energy. A system can be built using cheap and abundant materials, such as plastic and metal. It is simple to operate and maintain. It can supply a certain amount of steady (base load) power. It also doesn't require fancy solar cells, complex mirrors, or expensive water-cooling systems [11]. Apart from working on a very simple principle, solar chimneys have a number of special features:

1. The collector can use all solar radiation, both direct and diffuse. This is crucial for tropical countries where the sky is frequently overcast.
2. Due to the soil under the collector working as a natural heat storage system, updraft solar chimneys can operate 24 h on pure solar energy, at reduced output at night time. If desired, additional water tubes or bags placed under the collector roof absorb part of the radiated energy during the day and release it into the collector at night. Thus solar chimneys can operate as base load power plants. As the plant's prime mover is the air temperature difference (causing an air density difference) between the air in the chimney and ambient air, lower ambient temperatures at night help to keep the output at an almost constant level even when the temperature of natural and additional thermal storage also decreases without sunshine, as the temperature difference remains practically the same.
3. Solar chimneys are particularly reliable and not liable to break down, in comparison with other power plants. Turbines and generators - subject to a steady flow of air - are the plant's only moving parts. This simple and robust structure guarantees operation that needs little maintenance and of course no combustible fuel.
4. Unlike conventional power stations (and also some other solar-thermal power station types), solar chimneys do not need cooling water. This is a key advantage in the many sunny countries that already have major problems with water supply.
5. The building materials needed for solar chimneys, mainly concrete and glass, are available everywhere in sufficient quantities. In fact, with the energy taken from the solar chimney itself and the stone and sand available in the desert, they can be reproduced on site.
6. Solar chimneys can be built now, even in less industrially developed countries. The industry already available in most countries is entirely adequate for solar chimney requirements. No investment in high-tech manufacturing plants is needed.
7. Even in poor countries it is possible to build a large plant without high foreign currency expenditure by using local resources and work-force; this creates large numbers of jobs while significantly reducing the required capital investment and thus the cost of generating electricity [115].

IX. CONCLUSION

Solar chimney power plants are an interesting alternative to centralized electricity generation power plants. It is an ideally adapted technology for countries that lack a sophisticated technical infrastructure, where simplicity and uncritical operation of the installation is of crucial importance. A detailed literature survey of this system was performed. The review discusses the principles and characteristics of such a system, its requirements, its construction and its operation. It gives also a brief overview of the present state of research at the solar chimney power plant and future prospects for large-scale plants.

This paper showed that few prototypes have been tested in the world. It can be concluded that such systems need to be very large if they are to generate significant quantities of power. Because of high construction cost of solar chimney, many researchers have chosen the numerical way in their studies especially CFD methods.

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