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Solar Chimney Power Plant - A Review on Latest Technological Advances for Performance Enhancement

Sreelekha Arun
Faculty of Electrical and Mechanical Engineering, College of Military Engineering, Pune, India

Abstract: The energy consumption on global scale is continuously increasing, resulting in rapid use of energy resources available. Solar chimney power generation technology hence began to get growing attention as its basic model needs no depleting resources like fossil fuels for its functioning but only uses sunlight and air as a medium. It takes the advantage of the chimney effect and the temperature difference in the collector that produces negative pressure to cause the airflow in the system, converting solar energy into mechanical energy in order to drive the air turbine generator situated at the base of the chimney. Solar Chimney Power Plant (SCPP) brings together the solar thermal technology, thermal storage technology, chimney technology and air turbine power generation technology. However, studies have shown that even if the chimney is as high as 1000 m, the efficiency achievable is only around 3%. Hence, this review paper intents to put together the new technological advancement that aims to improve the efficiency of SCPP.

I. INTRODUCTION

This Human civilization is very closely intwined with energy, and it will be more so in future on the path of global development. The energy consumption on global scale is continuously increasing resulting in rapid use of energy resources available. The usage of energy in terms of fossil fuels are non-sustainable and also pose significant challenges in terms of environmental as well as health issues.

The scientific community and researches round the world are hence very keenly striving to address these issues. Power generation through environment-friendly methods using renewable and sustainable energy would prove to be good alternative in striking the right balance between growing energy demands, environmental concerns and health parameters.

Renewable energy technology is best when it is simple, reliable and as far as possible accessible to the technologically less developed countries as well. One such technology is the Solar Chimney Power Plant, which combines the two almost very widely available form of renewable energy that is solar and wind. These two forms of energy systems can be well harvested as they have the advantage of being clean sources with no emission issues during their operation.

II. PRINCIPLE

The Solar Chimney Power Plant has a simple constructional setup that comprises of solar air collector, chimney/tower, and wind turbine(s) with generator(s) coupled as power conversion unit. The solar air collector is a large glass covered area through which the solar radiation first passes, hits the ground that gets heated and subsequently heats up the air in between the collector and the ground. As the temperature of the air increases its density decreases and light air begins to rise up the tower.

The buoyant air that rises up into the chimney of the plant draws in more air from the collector perimeter thus enabling the convection process to happen more rapidly. The pressure difference between the column of cold air outside and the column of hot air inside the chimney acts as a driving force to maintain an updraft in the tower. The kinetic energy contained in the updraft results in rotation of the wind turbine situated at the base of the tower producing mechanical energy which in turn drives the generator which produces electric energy.

The schematic diagram of Solar Updraft Tower or SCPP and a pictorial representation with thermal imaging of selective air currents are shown in Fig 1 and Fig 2 respectively. Electrical output of a solar updraft tower is proportional to the volume included within the tower height and collector area (Fig 3.). The same output may result from a larger tower with a smaller collector area and vice versa.

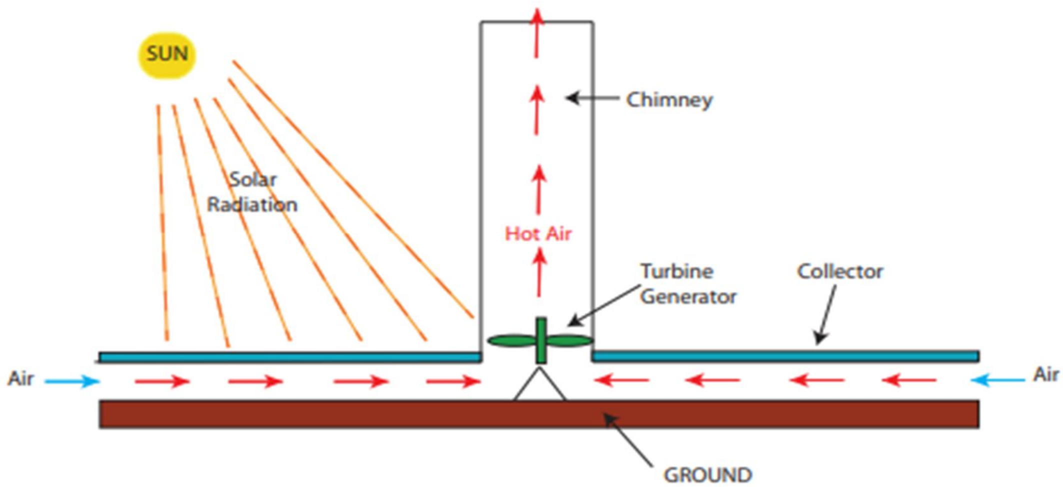

Fig 1: Solar Updraft Tower Schematic Diagram [1]

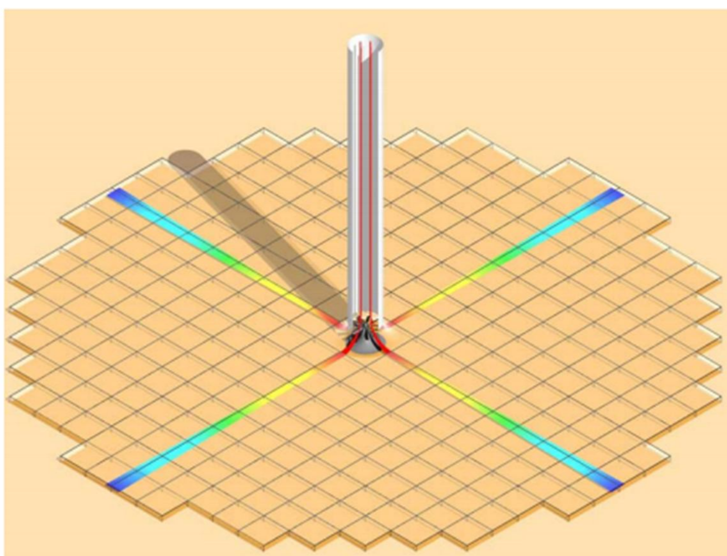

Fig. 2 Pictorial representation with thermal imaging of selective air currents in SCPP [2]

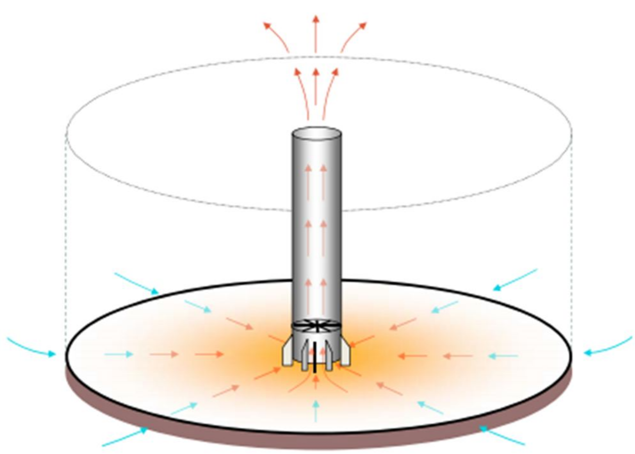

Fig 3. Electricity generation of a solar updraft tower in proportion to the volume defined by tower height and collector diameter [2]

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III. HISTORY

The Solar Updraft Power generation was first proposed in 1903 by the Spanish Colonel Isidoro Cabanyes (Cabanyes, 1903) [1]. His apparatus consisted of an air-heater attached to a house with a chimney. Inside the house, there was a wind propeller for electricity production. Another early description can be found in the work of the German author Hanns Günther (Günther, 1931). This name is just the pseudonym for Walter de Haas. In 1931, in his most important book ("In hundert Jahren - Die künftige Energieversorgung der Welt" – "In a hundred years: the world's future energy supply") he wrote that the humanity would have run out of petrol and coal, so he went through other sources of energy. He wrote about some renewable energy technologies already existing at that time (e.g., geothermal power), and then he also mentioned the solar updraft tower. The idea of the author was a solar chimney on the slope of a mountain. The very high air speed could deliver an enormous amount of energy which could be extracted by means of wind turbines.

Around 1975, a series of patents were granted to the US engineer R.E. Lucier in countries with deserts suitable for SUPPs [1], like Australia, Canada, Israel and the US. These patents concerned: "Apparatus for converting Solar to Electrical Energy", "Utilization of Solar Energy", "System and Apparatus for Converting Solar Heat to Electrical Energy", "System for converting solar heat to electrical energy".

Based on detailed theoretical preliminary research and a wide range of wind tunnel experiments Schlaich Bergermann 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 (Fig 3), with funds provided by the German Ministry of Research and Technology (BMFT) [2]. Subsequently, many studies have been carried across the globe in terms of experimental setups, mathematical models as well as prototype versions to understand the working and dependent parameters to enhance the performance of the Solar Chimney Power Plant and to make it commercially viable.

Fig 4. Prototype of the solar updraft tower at Manzanares, Spain [2]

IV. GENERAL ADVANTAGES

The simple and basic form of Solar Chimney Power Plant comes with some key advantages which will work in the favour of the system in gaining popularity.

A. The collector is capable of absorbing both direct and diffuse solar radiation which beneficial when the sky is overcast.
B. The solar radiation that hits the ground after passing through the collector surface, is stored in the form of heat energy in the soil. The soil thus acts as natural heat storage system which can release the heat even during the night. Hence power can be made available even at night at reduced output though.
C. This system is less susceptible to wear and tear, as turbines and generator are the only moving parts, making the system more reliable and robust.
D. As there is no combustion requirement, the fuel consumption is nil resulting in zero emissions.
E. This technology can be very easily adopted in arid areas where water scarcity is observed, since the system does not have any cooling water requirement.
F. It does not demand any special material for its construction and hence can be built with commonly available materials like concrete and glass. This makes it possible to build this plant with reduced capital cost with lesser electricity generation cost.

However, the issues of availability and accusation of large area of flat land and that too at affordable price may cause an initial hindrance in setting up the plant.

V. TECHNOLOGICAL ADVANCES/IMPROVISATION FOR ADDITIONAL OUTPUT

Apart from the above-mentioned base system, there are various latest enhancement studies carried out which turns out be an added benefit in terms of either improving the system performance or additional product output. Some of these advances are discussed further.

A. Performance Enhancement Strategies of a Hybrid Solar Chimney Power Plant Integrated with Photovoltaic Panel

ZThe solar chimney power plant performance was studied with integrated photovoltaic panel under varying design configurations of collector duct and solar chimney[3]. The performance of the solar updraft plant with incorporated PV panel has been substantially enhanced by two ways: a. Tapering the collector flow passage; b. Divergent chimney by increasing cross-sectional area of the chimney outlet and it was observed that there is a suitable combination of duct convergence and chimney divergence which gives best performance of PV and turbine power output. The study was carried out using an experimentally validated numerical model to study the PV panel cooling and turbine power output.

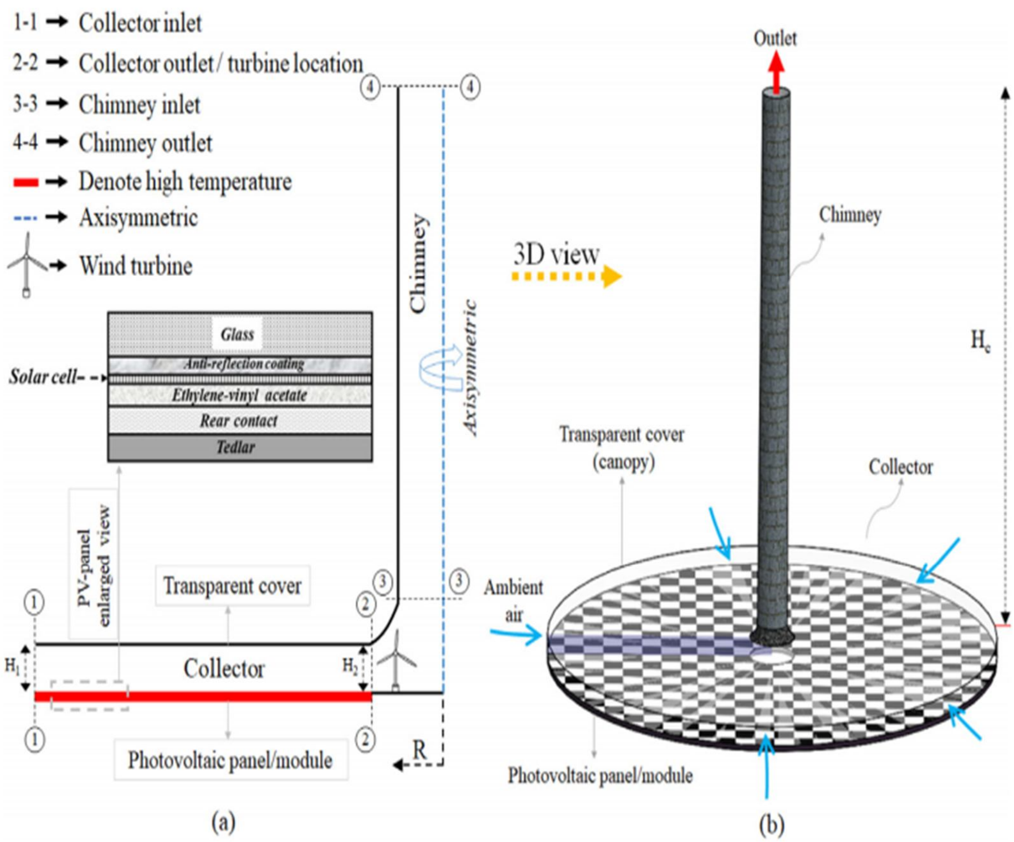

Fig. 5 Schematic diagram of a new hybrid solar chimney power plant: (a) Two-dimensional axisymmetric model; (b) Three-dimensional view of computer aided design (CAD) model after 360° rotation [3]

The hybrid system was investigated for values ranging for collector taper ratio (TR) between 0.34 and 1, while chimney outlet to inlet radius ratio (CORR) was between 1 – 5. It was found that initially, with increase in the chimney outlet radius for CORR 1.5- 3 performance improved. It was also observed that at this value, the flow velocity was considerably enhanced by 121%, and hence correspondingly increasing the turbine power output by 363%. The PV panel efficiency also increased by about 4%.

These studies revealed that neither the divergent chimney nor a tapered collector duct design alone were sufficient to enhance the system performance when integrated with the PV panel. The combination of suitable design changes in both collector and chimney seems the best design strategy for hybridization of solar chimney system. It was also observed that high electrical efficiency of PV panel was observed around 7% with taper ratio 0.34 and CORR = 3 and about 80% of the collector area near the chimney was the most influential region for cooling of the PV panel, where a consistent temperature drop of 10–12 °C was observed. This helped in reducing the surrounding high temperature which is generally responsible for lower electrical conversion efficiency in a PV module.

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B. Solar Chimney Power Plant Integrated with Transparent Photovoltaic Cells and Desalination Method

The conventional Solar chimney power plant (CSCP) was compared for its performance by incorporating two concepts of Photovoltaic cells (PVSCP) and Desalination (PVDSCP) process. Mathematical models were developed for each configuration to carry out the comparative study [4]. The schematic for this novel idea is shown in Fig 6.

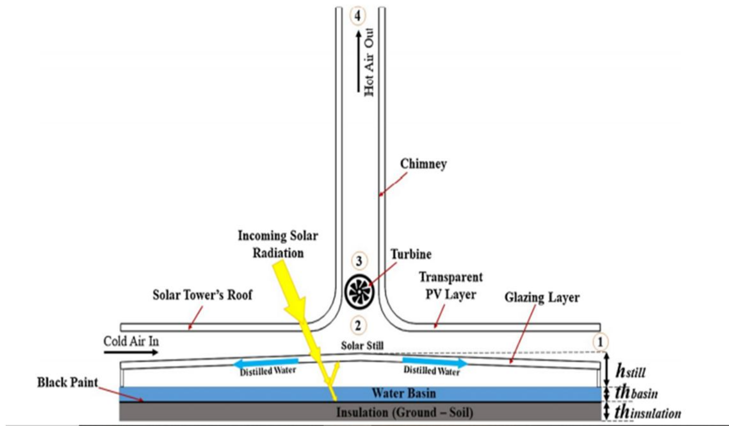

Fig. 6. Schematic of Photovoltaic and Desalination based Solar Chimney Plant cross section [4]

It was observed that proposed configurations were effective as the collector efficiency has improved considerably by about 4.21% and 26.13% for PVSCP and PVDSCP respectively compared to CSCP. Accordingly, plant efficiency increased by about 8.54% and 53.06% for PVSCP and PVDSCP respectively compared to CSCP as a result of substantial improvement in the collector efficiency.

Also, the turbine power output for the PVSCP is the highest and is larger by about 17.9% and 31.3% compared to CSCP and PVDSCP respectively. PVDSCP showed the lowest turbine power as a large portion of solar radiation passing through the transparent PV roof is absorbed by the water and bottom plate for desalination purpose by evaporation and less amount of energy is left for expansion in turbine.

An added advantage of the PVDSCP system is that it generates significant amount of fresh water in the order of about 14.6 T/ hr which can be used very effectively in places where saline water is more in comparison to fresh water.

The paper also studies effect of geometrical parameters on collector and plant efficiency and also on turbine and total power. While increase in chimney radius does affect the efficiency and power outputs significantly, increase in collector radius brings down the collector and plant efficiency drastically but improves the PV and overall power output of the plant owing to the increased collector surface area. While increase in roof/ collector height does not affect the efficiencies much, it does have marginal improvement in the turbine power and hence total power. Increasing chimney height however contributes significantly to increase in efficiencies and power output.

C. Solar Chimney Power Plant Incorporating Double Roof collector Design Method

Novel idea was proposed in a study, wherein Double Roof concept was introduced to improve the collector efficiency of Solar Chimney Power Plant [5]. CFD methodology was used to compare between three models; conventional collector, double-pass collector with parallel flow and double-pass collector with counter flow as seen in Fig 7.

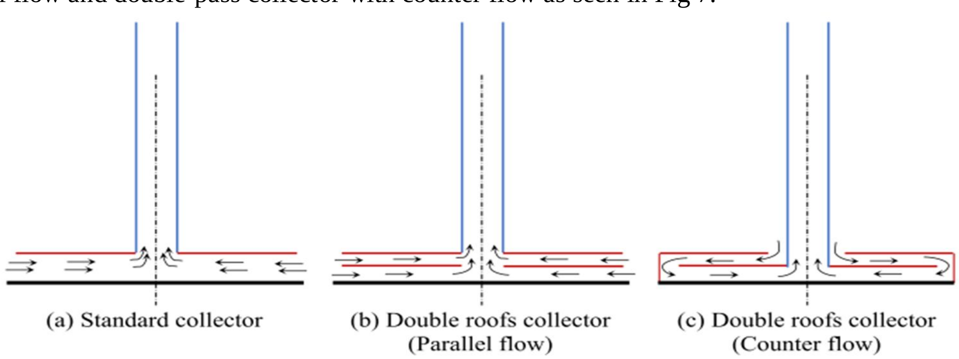

Fig. 7. Schematic of the proposed Double roof collector SCPP designs [5]

It was observed that the total radiant load passing through the collector was found to be higher in the double roof method, as the radiation wave increases under the collector, the amount of the accumulated energy in both types of double roof collectors immensely increases thus resulting in a remarkable difference in the optical behaviour of these configurations.
It has been observed that the counter flow collector gives the high output thermal energy in comparison to other types. According to the analysis, it is clear that the high air temperature in the chimney appears in the counter flow collector while the weakest values appear in the chimney coupled with single pass collector. While the mass flow rate in the Parallel type is larger, the counter flow collector presents the best option in terms of heating process. It is also observed that counter flow collector presents the high velocity values along the chimney while the lowest air velocity appears in the standard case. The proposed designs aim mainly to enhance the collector efficiency. The increase in the collector efficiency in double pass mode is due to the increase of the heat removal from two flow passages compared to one flow pass in the standard collector. The temperature rise in the collector increases by 16% and 24% respectively, in the parallel flow system and the counter flow systems. Comparing to the standard configuration, the counter flow system increases the collector efficiency by 25.8%. and an efficiency rise by 19.4% appears with the parallel flow collector. The highlights of this study are that the addition of a second roof in the collector increases the temperature and the velocity of the fluid through the system. Also, an important finding is that the parallel flow collector with large height of the second roof has more efficiency while the counter flow collector with small roof height can be considered as the best option.

D. Solar Chimney Power Plant Incorporating Radial Partition Walls in the Collector

Comparing three methods: one with a conventional horizontal canopy; one with a familiar sloped canopy design; and one with eight radial partition walls (RPWs) as depicted in Fig. 8 uniformly distributed under the collector canopy, was carried out in a study [6]. RPWs was found to be the best design to sustain the largest driving force in the chimney, with the sloped canopy design coming in second. The driving force of the plant decreases to a minimum value and then gradually increases with increasing ACW (ambient cross wind) velocity.

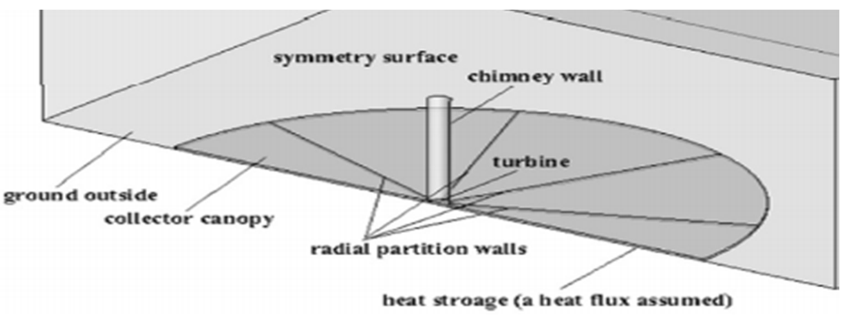

Fig. 8 Three-D geometrical model of SUPPS with RPWand surroundings [6]

The important observations made in this study were that RPWs improves the performance of the plant by preventing the heated air in the compartments from escaping into the environment without driving the turbine and also by harnessing some of the available wind energy. When comparing the output power of the different designs, the RPWs design is slightly better than the sloped canopy design under most conditions while it was observed that a combination of these two designs would further improve the system performance.

E. Solar Chimney Power Plant Design Aided with Reflectors

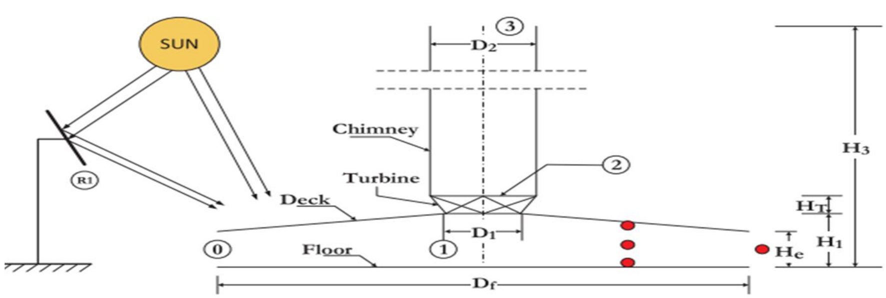

Figure. 9. Schematic diagram of the experimental setup with mirrors (i) 0, Collector Inlet, (ii) 1, Collector Outlet and Turbine Inlet, (iii) 2, Turbine Outlet, (iv) 3, Chimney Outlet, (v) Thermocouples and (vi) R1 Reflector. [7]

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A new design of a solar chimney power plant (SCPP) incorporating reflectors as shown in Fig. 9 was used to enhance incident solar radiation, in a study carried out [7]. It was shown that this improvisation using reflectors enhanced the efficiency and power output by 22.61% and 133%, respectively compared to traditional SCPP. The mirrors were placed around the deck, in a circular pattern such that it resembled a field of heliostats uniformly reflecting radiation towards the deck. They are placed in such a manner that all the radiation falling on a mirror is reflected to the deck. The deck could receive maximum direct radiation due to reflection from a mirror.

For the assumed SCPP model aided with reflectors, the gain in temperature of the floor and the mass flow rate is increased by 9.89% and 134%, respectively, when compared with SCPP. The yearly average energetic efficiency of an SCPP was found to be 0.641% and 0.523% with and without reflectors, respectively.

F. Artificial Roughness Created for collector for Performance Improvement of SCPP

Study was carried out by to investigate the effect of artificial roughness on the performance of SCPP [8]. Comparison was carried out between SCPP with and without artificial roughness for the weather conditions of Semnan, Iran using 3-dimensional simulation. In this simulation, in the energy storage layer, some artificial roughness is placed, and the cross-section of this roughness was considered as a rectangle as shown in Fig. 10.

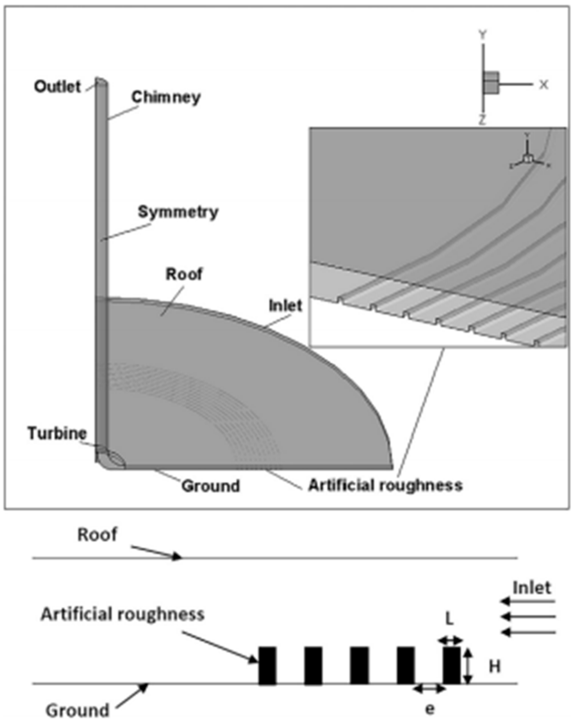

Fig. 10 Diagram of the SCPP with the artificial roughness [8]

The velocity at the inlet of the chimney for different roughness heights for constant roughness length was observed. Change in velocity was seen at the inlet of the chimney in the no-load condition (without turbine operation) and were compared with the velocity in “without roughness and no-load” condition. Incorporating artificial roughness resulted in velocity decreases by adding artificial roughness. The main reason of the velocity reduction was the friction increase. By increasing height, first, the velocity increases and then decreases. An optimal dimension for the roughness geometry would help the power plant perform better. The highest variations in velocity are around 1.8%. It was also seen by increasing turbine pressure drop, there was a greater difference in power which occurs between SCPP with and without artificial roughness. The fluctuations of velocity and temperature increases by increasing the height of artificial roughness for constant roughness length because the turbulence of the flow field increases due to presence of rough surface. Increasing the roughness dimensions results in improved flow disturbances and thus improves heat transfer. The highest temperature rise is 1.2 percent.

It was also found that the location of this roughness could also affect the performance of the SCPP. The roughness near the collector entrance has the best impact rather than the roughness in the middle of the collector or in the chimney inlet.

G. Dimension Optimisation for SCPP and its Economic Implications

Study was carried out to identify the key parameters that drive performance of SCPP and it was assessed in terms of power output and power output per cost using a detailed thermodynamic model as shown in Fig.11 considering plant dimensions such as the collector diameter and chimney height and radius [9]. It was reconfirmed that the dimensions of the main components must be well matched to achieve best performance.

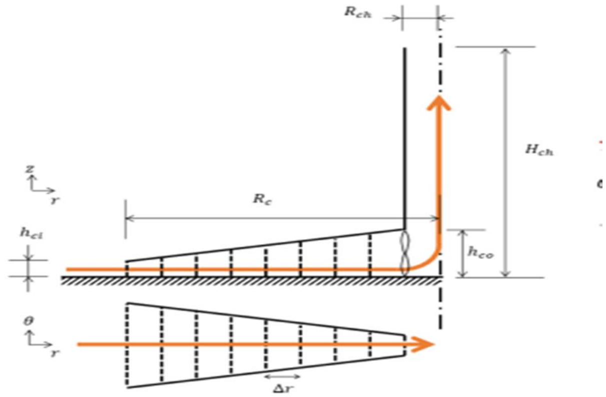

Fig 11. Schematic diagram of plant cross-section and plan view [9]

It was observed that electricity generation initially increased linearly with collector radius and chimney radius, before plateauing off or reaching a maximum. While the power output increased quadratically with chimney height, it was also seen for a given chimney height, the collector size must be carefully matched with the chimney radius. Study also revealed that narrow chimneys constrict the flow and consequently limit power output, hence chimney radii of up to 200 m were necessary to reach power output of 900 MW.

Optimisation of power output coupled with the cost model indicated that several smaller plants with collector radius of about 3000 m may be advantageous over one larger power plant. Also, taller chimneys become economically beneficial until the specific chimney costs increase more than quadratically with height.

H. Phase Change Material used for Performance Enhancement Implications of SCPP

Phase change material was used to investigate the performance of a laboratory solar chimney using a prototype having a chimney 0.3 m in diameter and length of 12 m and an air collector with the diameter and height of 11 m and 0.65 m, respectively as depicted in Fig. 12. Experiments were conducted [10] to record changes in temperature of intake air, ground, and air trapped within the collector in addition to speed alterations of intake air in three modes of utilizing soil, water and paraffin as a thermal storage material. Time productivity increased by 9% and 20% while the electric energy production also increased by 6.2% and 22%, for water and paraffin respectively in comparison to no absorber state (only soil) in this solar power plant.

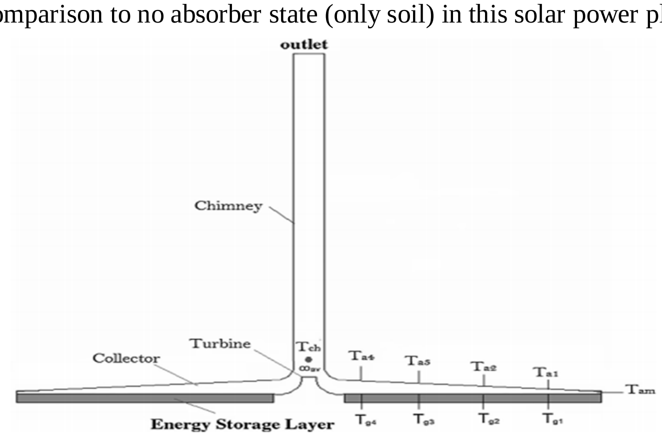

Fig.12 Experimental set-up with Energy Storage layers and Temperature sensors [10]

It was also observed that the amount of electrical energy generated from the experiment utilizing paraffin as a thermal absorber is more than those of the other two experiments, which was about 11.5 kWh/day. Also, by analysing results of errors and sudden changes in radiation, it was found that paraffin provides a stable state for this power plant model.

I. Wind Supercharged SCPP (WS-SCPP)

An unpowered wind pressure wheel at the chimney top was set up to act as wind supercharger and study was carried out to understand its effect on SCPP performance and its cost implications [11]. The unpowered wind pressure wheel is made of the H-vertical axial wind wheel blades and ventilator blades as shown in the structural diagram Fig.13. The high-altitude wind energy belt rotates the H-vertical axis wind wheel, and the wind wheel turns the ventilation blades to generate negative pressure. This increases the pressure difference between the inside and outside of the chimney, strengthens the chimney effect and in turn increases the pumping force, accelerates the discharge of hot airflow inside the chimney. At the same rotational speed, the shaft power of WS-SCPP is always higher than that of SCPP. All this results in an increase in the power generation with no extra power supply.

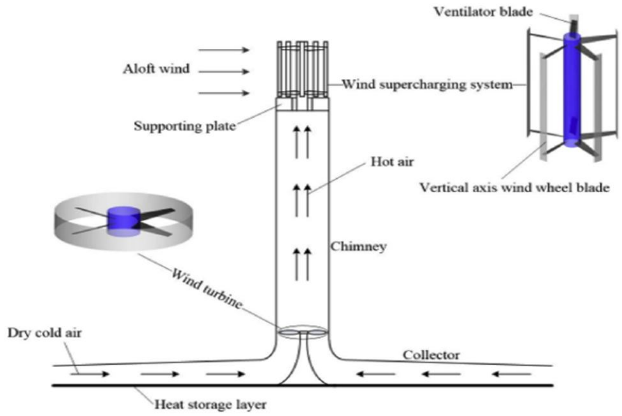

Fig.13 Structural diagram of WS-SCPP [11]

The SCPP with different chimney heights were numerically simulated to obtain the turbine shaft power increment and the corresponding negative pressure increment in the chimney. It was observed that when the stack height increases to 280m, the power generation can reach 56 kW, and the increment of negative pressure is 63.1Pa. This showed that the stack height of the SCPP based on the Spanish prototype has to increase by more than 80m to produce the same negative pressure increment and power generation effect as the WS-SCPP. From the economical aspect it was observed that the Net Present Value (NPV) of SCPP was less than 0 for the first four years and then greater than zero during service, while the NPV of WS-SCPP is always greater than zero during service time. The net income and NPV of WS-SCPP are always higher than that of SCPP which reflects the superiority in economic performance of WS-SCPP.

J. Solar Chimney Power plant Performance Influenced by Canopy Condensate Formation

Dust and/or condensate film present on the cover affects the transmissivity of solar radiation through the transparent canopy/cover of solar collectors. Study was conducted to understand its influence on collector and solar chimney performance [12] as shown in Fig.14. It was observed that radiation transmittance was considerably reduced from 7:30 a.m. until 10:30 a.m. due to the due to presence of dew resulting in condensate formation which showed about 9% - 10% variation in solar radiation transmittance was found between dry and wet canopy. Also, a part of the heat energy was utilised in evaporation of the condensate. These reasons caused delay in energy conversion process.

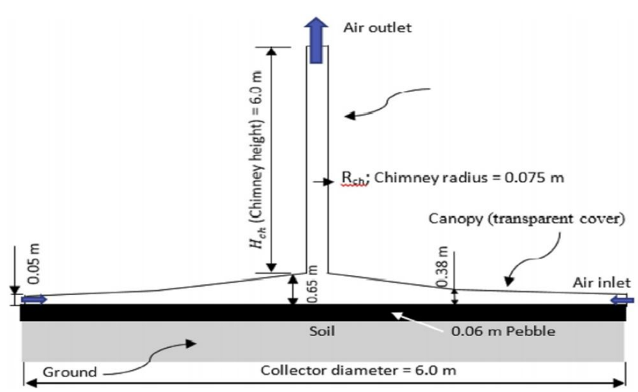

Fig 14. Schematic of the solar chimney model built to study the influence of condensate on canopy [12]

The air temperature rise, with presence of condensate, was delayed and reduced by 12.0%-14.0% compared to a surface without condensate. An auxiliary heat source that supplies heat before sunrise was found to be necessary to evaporate the condensate film and allow the solar chimney to operate early. The presence of condensate on the canopy surfaces also resulted in accumulation of dust particles and mud on the surface, thereby further reducing the chimney performance.

It suggested the need of future research which would be directed to create suitable techniques that eliminate condensate formation on the canopy of the solar collector of a solar chimney power plant.

VI. CONCLUSIONS

The market for Solar Updraft Towers according to the reference scenario of the latest IEA World Energy Outlook, world electricity demand will grow at an average annual rate of 2.5% to 2030. Hence about 4800 GW of new capacity between now and 2030 are needed to meet the projected increase in electricity demand and to replace ageing infrastructure. In this gigantic market, Solar Updraft Towers have to compete against conventional power plants and against other types of solar power plants as well. According to the reference scenario, the use of non-hydro modern renewable energy technologies (including solar) sees the fastest rate of increase until 2030. The share of non-hydro renewables in total power output is expected to rise from 2.5% in 2007 to 8.6% in 2030. As the annual global horizontal radiation is approximated around 1800 kWh/m² in areas with sufficiently high solar radiation, especially those in the sun belt of the earth, i.e., the zone about 35° north and south of the equator, are suitable for solar updraft towers. Future scope shall be to study the feasibility and commercial viability of these technological modification so that the solar chimney power system can be taken up for production and installation on a large scale.

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